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REVIEW OF DEMILITARISATION AND DISPOSAL TECHNIQUES FOR MUNITIONS AND RELATED MATERIALS

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1. EXECUTIVE SUMMARY

Demilitarisation is an increasingly important aspect of munitions management. With a drive for higher performance and greater safety, new munitions and fillings render old munitions obsolete and munitions stockpiles cost money both to establish and maintain so surplus munitions are an unwelcome expense and potentially a risk. The process of disposal is being shaped by a number of factors. Foremost is increasingly stringent environmental regulation restricting and modifying the methods. But other factors are also significant such as transhipment regulation, restrictions on proliferation of conventional weapons, and resource recovery either through financial pressure or policy. The result is a menagerie of demilitarisation techniques – sometimes complementary, sometimes competing – that this paper provides an overview of.

All munitions have a finite service life and will at some stage need to be either expended or disposed of. Disposal can involve dumping, resale and demilitarisation. Dumping is banned at sea as a result of the London Convention and related agreements. Dumping on land is severely restricted if not banned in most jurisdictions. Resale is an attractive option in terms of recovering value from munitions however munitions must be serviceable to resell and this option is restricted by issues of proliferation and security. This leaves demilitarisation as the primary method of disposal. Demilitarisation means removing or otherwise neutralising the military potential of an item, in this case a munition. This may or may not involve the destruction of the munition but it does require that the energetic material is destroyed or converted.

1.1 ENVIRONMENTAL IMPACT

For environmental impact, three major types of demilitarisation can be considered: uncontained thermal treatment such as Open Burning and Open Detonation (OB/OD); contained industrial thermal treatments such as incineration; and other industrial treatments such as oxidation and biodegradation.

OB/OD is a simple and widely practised technique however it is under increasing pressure from environmental regulators and has been banned in a number of countries and states. The impacts of OB/OD are air emissions, residual material (either energetics or toxic materials such as heavy metals) and noise. A large amount of testing has been carried out into emissions and tools exist to estimate emissions from these demilitarisation activities. Depending on the nature being destroyed it is possible for OB/OD to meet the emissions requirements set on incinerators, with open detonation likely to be a cleaner process. Residual material can cause issues in groundwater contamination and personnel safety. Site characterisation of OB/OD sites has found that the effect varies widely however correct design and procedures at the OB/OD site, such as burning pads, helps to reduce the environmental impact. Noise, from open detonation in particular, is difficult to mitigate and is frequently a limiting factor.

Contained industrial thermal treatments, such as incineration, offer a means of treating emissions and of introducing a controlled industrial process. The primary environmental impact is air emissions. These are subject to control by environmental regulators and both the European Union and the United States have recent and broadly similar regulations. Significant differences occur in the requirement of destruction efficiency in the US, different categorisations of metal emissions and the regulation of acidic gases in Europe. Using pollution control systems, demilitarisation incinerators in many countries meet these stringent regulations however it imposes and additional cost, particularly in meeting nitrogen oxides emission levels set by the European Union.

Other industrial treatments such as oxidation and biodegradation produce a similar range of environmental hazards to incinerators. Noise can be an issue but is not generally worse than other industries. Solid waste will be produces, such as fly ash from incineration, and this may or may not be hazardous. Any process involving water will produce waste water. This can be reduced by closed cycle reclamation systems but explosives contaminated water remains a major issue. A significant distinction between techniques is whether waste can be easily disposed of or whether further treatment is required.

1.2 TRANSPORTATION

Munitions are transported as dangerous goods under the UN classification system. There is the potential for munitions to be demilitarised to be classified as hazardous waste which carries a different set of requirements for transportation and storage. In the US, this issue has been clarified through the Military Munitions Rule which sees munitions for demilitarisation transported and stored in accordance with Department of Defence regulations. In other jurisdictions this issue has not been directly addressed in this manner. A side effect of classifying munitions as hazardous waste would be the application of the Basel Convention. This regulates the transhipment of hazardous waste and the Ban Amendment (which has not yet entered into force but is incorporated into European Union legislation) prevents the shipment of hazardous waste to developing countries. Although the Basel Convention would introduce an additional level of administration it would not necessarily affect the current demilitarisation industry which is centred in Western Europe and the US.

1.3 METHODS OF DEMILITARISATION

The demilitarisation process consists of the following steps:

- Transport to the demilitarisation site;
- Unpacking from transportation packages;
- Disassembly;
- Removal of Energetics;
- Destruction; and
- Resource Recovery and Recycling (R^3).

Disassembly techniques are aimed at accessing the energetic material, removing items such as fuzes for alternative disposal methods and breaking down the munitions to meet the requirements of latter treatment. Disassembly can be conducted manually or with robotic assistance. Alternative techniques such as abrasive waterjet cutting and cryofracture allow access to the energetic material in a safe manner on a wide range of munitions. The energetic material may require size reduction in which case a technique such as cryocycling could be considered.

Removal techniques are aimed at removing the energetic material from the munitions casing allowing the munitions casing to be recycled or discarded and the energetics to be treated. Some processes do not require removal of the energetic as they are destroyed in situ, for example open detonation. Techniques for removal fall into two major categories, washout techniques using a high pressure jet to abrade the energetic material and meltout techniques which rely on the heating of meltcast explosives to remove the filler. One of the key drivers of research in removal techniques is to reduce the production of waste water which requires further treatment. As a result, fluids other than water have been used for washout and some meltout techniques use indirect heating such as microwave, induction and autoclave meltout.

Destruction of the energetic material is a key requirement in demilitarisation as it is the energetic material which most particularly gives munitions their military potential. Thermal techniques as already discussed include open burning and open detonation as well as incineration. A number of variants attempt to address particular issues. Thermal techniques can generally handle complete munitions or require limited pre-treatment. The second major class of destruction technologies are oxidation techniques. These utilise a variety of methods include pressure, heat and oxidising agents to mineralise the organic components in the explosive. They vary in the operating conditions and the types of wastes they can treat and will normally require removal of the energetic material. Finally, biodegradation utilises microbes to break down organic compounds. Oxidation and biodegradation generally produce waste streams that require further treatment, possibly by other oxidation or biodegradation techniques.

The components of the demilitarised munition may be disposed of but there are many opportunities to apply Resource Recovery and Recycling (R^3) techniques. R^3 can reduce costs by recovering value from the munitions and is important in the government policies of most nations. Thermal methods can apply R^3 through recovering waste energy and through sale of scrap metal. An advantage of other destruction methods is that the energetic material can be converted for other uses. Typical uses include recycling as fertiliser or conversion to commercial chemicals. Reuse is also possible where the energetic material is not destroyed at all but instead is reused as commercial explosive, propellant or requalified as military explosive.

This paper covers the issues or environmental impact and regulation transport regulation and the techniques of demilitarisation in greater detail. It is extensively referenced to provide a literature review of the topic and it also contains a list of organisations and companies involves in demilitarisation.

2. INTRODUCTION

In the context of munitions, demilitarisation

> *… refers to the act of removing or otherwise neutralizing the military potential of a munition. Such neutralization is to be carried out in a safe, cost effective, practical and environmentally responsible manner. Demilitarization is a necessary step for military items prior to their release to a non-military setting.* [1]

Conceptually, the demilitarisation process can be though of as having the following steps:

- Transport to the demilitarisation site;
- Unpacking from transportation packages;
- Disassembly – this involves breaking down the munition in some manner;
- Removal of Energetics;
- Destruction – normally of the energetics but other elements of the munition can be destroyed as well; and
- Resource Recovery and Recycling (R^3).

Not all of these steps are required, for example, munitions could be destroyed with out disassembly or removal of energetics. Destruction and R^3 techniques can be combined as different components of the munition may be suited to different techniques. Additional steps may be required such as size reduction or the generation of a slurry in order to allow treatment. The basic process is illustrated in Figure 1.

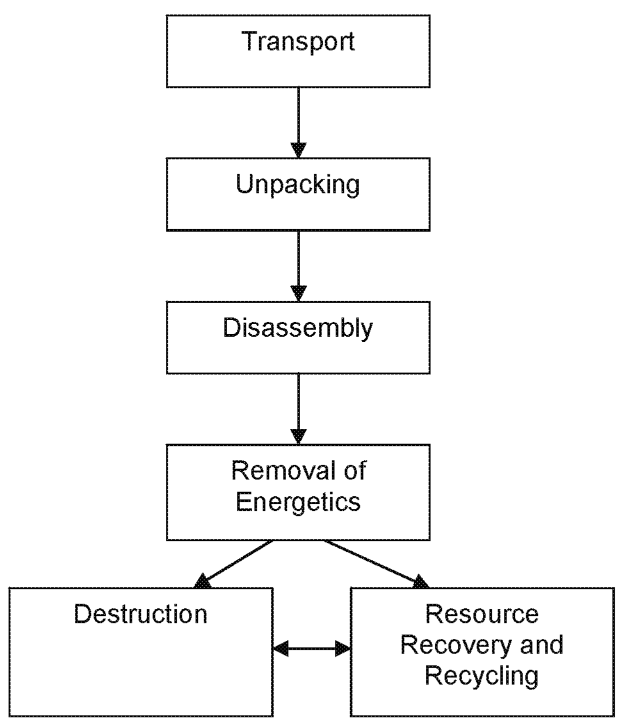

Figure 1 – The Demilitarisation Process

All munitions have a finite lifetime. They can reach the end of their lives through ageing processes or deterioration, they can become obsolete by developments in weapons systems, they can become surplus due to changes in requirements or they can be required to be destroyed due to international treaties and agreements. Storage of these munitions can be costly, and potentially hazardous for munitions that have reached the end of their service life.

Demilitarisation is not the only option for disposal of munitions. Often they can be expended in training in preference to munitions with greater life remaining. Obsolete or surplus munitions could be sold to other countries. Nonetheless, it is not possible or desirable to dispose of all munitions this way, therefore a significant quantity are demilitarised. The stockpile of munitions for demilitarisation in western countries probably amounts to in excess of half a million tons. In 2002 the US stockpile alone amounted to 453 000 tons.[2] Significant stockpiles exist in other countries where they are not only a safety hazard but can be destabilising and at risk of usurpation for illegal or terrorist activities.

Advances in demilitarisation were precipitated by the end of the Cold War. This led to dramatic reductions in force levels and increases in the demilitarisation stockpile. For Europe, industrial scale demilitarisation was started as serious industry by German reunification in 1990. This left the new German government with a large stockpile of ex-East German Army munitions that needed to be destroyed. This provided the impetus for a number of German firms to begin industrial scale demilitarisation. Other European countries have subsequently developed considerable industrial demilitarisation capabilities. In the United States, increasing environmental restrictions and a push for more recycling and waste prevention by the Federal government[3] has seen a steady program of research into demilitarisation and the development of greater industrial demilitarisation capacity.

As a result of these changes it is timely to review the current status of demilitarisation techniques. The paper will be a literature review of the technology involved in demilitarisation, the legislation and regulation that impacts upon it as well as a summary of the organisations involved in demilitarisation.

The main body of the paper begins with section 4 covering environmental impact and regulation of demilitarisation activities. This is one of the main drivers of change in the demilitarisation of munitions and, although some aspects are peculiar to particular techniques, the issues involve affect all demilitarisation activities. Likewise, section 5 covers transport regulation and in particular the issue of hazardous waste classification and is applicable to all demilitarisation techniques.

Section 6 covers particular demilitarisation techniques and technology. Each technique is briefly described along with its application and some evidence of its use or state of research. Finally, section 7 is a summary of the major organisations and companies involved in demilitarisation research or activities.

A number of topics are outside the scope of this paper. In particular, this paper will not cover:

- Design of munitions for demilitarisation – for an overview of this topic see Stalker's paper to the NATO Research Technology Organisation Applied Vehicles Technology Specialists' Meeting.[4]

- Demilitarisation of chemical or nuclear weapons – this topic is large and generates considerable literature. A good starting point is the International Chemical Weapons Demilitarisation Conference (see section 7.1.5)
- Explosive Ordnance Disposal – The series of NATO Allied Explosive Ordnance Disposal Publications (AEODPs) provide a starting point for this topic

This paper will not attempt to assess the merits of particular demilitarisation methods. This can only be attempted with knowledge of the particular munition natures, location and other constraints. It is also not a comprehensive survey of the literature on any particular technique; rather a number of significant references are given as a starting point. The paper is limited to utilising open and unclassified information. With few exceptions, all of the information is also published. Due to time constraints it was not possible to get feedback on the content from all relevant stakeholders.

3. GLOSSARY, ACRONYMS AND ABBREVIATIONS

3X – US level for explosives contamination – articles where surface contamination has been removed but sufficient contamination may remain in 'less obvious' places to present an explosive hazard.

5X – US level for explosives contamination – articles where there is not enough remaining contamination to present an explosive safety hazard.

AASTP – Allied Ammunition Storage and Transport Publication

Acid Gases – Sulphur dioxide (SO_2) and nitrogen oxides (NO_X) – these gases are the primary cause of acid rain, reacting to form sulphuric and nitric acids with atmospheric water.

ACWA – Assembled Chemical Weapons Assessment – a US programme to assess alternatives to the baseline demilitarisation process for assembled chemical weapons due to public concern regarding incineration.

AEODP – Allied Explosive Ordnance Disposal Publication

AFJ – Abrasive Fluid Jet – a high pressure fluid jet using abrasives to improve cutting performance.

ANFO – Ammonium Nitrate / Fuel Oil – a commercial blasting explosive.

AP – Ammonium Perchlorate (NH_4ClO_4) – a component of many rocket motor propellants.

APE – Ammunition Peculiar Equipment – codified equipment in the US for ammunition handling tasks including demilitarisation.

ARDEC – US Army Armament Research, Development and Engineering Center – based at Picatinny Arsenal, New Jersey.

ASJ – Abrasive Slurry Jet – a high pressure fluid jet using abrasives mixed into a slurry prior to reaching the nozzle.

AWJ – Abrasive Water Jet – a high pressure water jet using abrasives to improve cutting performance.

Bang Box – A series of US tests into OB/OD emissions.

BAT – Best Available Techniques – a requirement that environmental legislation puts on pollution control and waste treatment.

Black List – A means of controlling activities where all activities on the black list are not permitted. Compare with permitted list and grey list.

CAD – Cartridge Actuated Device – a small explosive loaded device extensively used in aviation. See also PAD.

CFJ – Cavitating Fluid Jet – a high pressure fluid jet where greater abrasive power is achieved by initiating cavitation in a medium.

CMS – Continuous Monitoring System – a component of a pollution control system where the emission s are continuously monitored and may be linked to plant shutdown conditions

Comp B – Composition of 60% TNT, 40% RDX and wax – a common meltcast explosive composition.

Demilitarisation – The act of removing or otherwise neutralizing the military potential of a munition.

Disposal – End-of-life tasks with a munition that may include demilitarisation.

Dumping – Disposal of munitions by means such as landfill or sea dumping, typically munitions have not been demilitarised.

DAC – Defense Ammuntion Center – US organisation that manages the Joint Demilitarization Technology Program.

DNT – Dinitrotoluene.

DoD – Department of Defense

EC – European Community/Commission/Council

EDB – Emissions Database – for OB/OD activities

EFF – Emission Fate Factor – a means of linking the quantity of a component in a munition with the resulting emissions using the EDB.

EIA – Environmental Impact Assessment

EIPPC – European Integrated Pollution Prevention and Control Bureau – publishes guidance on BAT for incineration.

EM – Energetic Material – a substance or mixture of substances, which by chemical reaction, is capable of rapidly releasing energy.

EPA – Environmental Protection Agency

EU – European Union

EWI – Explosive Waste Incinerator – a destruction technique.

Explosive D – Ammonium picrate (ammonium-2,4,6-trinitrophnolate) – an explosive with low impact sensitivity once widely used in US Naval shells.

FBC – Fluidised Bed Combustor – a combustor using blown air to improve combustion of a slurry or granular solid fuel.

FBI – Fluidised Bed Incinerator – an incinerator using blown air to improve combustion of a slurry or granular solid fuel.

FJ – Fluid Jet – a high pressure fluid jet used for ablation.

Flashing – Thermal treatment of scrap metal to ensure that no residual explosive hazard exists.

GAC – Granular Activated Carbon – Carbon (normally charcoal) that has been activated to greatly increase its surface area, used for waste water treatment.

Grey List - A means of controlling activities where all activities on the grey list are require specific permission. Compare with permitted list and black list

HESCO – The HECSO Bastion Concertainer, used for temporary barricading of potential explosion sites.

HP – High Pressure.

HMX – Cyclotetramethylene-tetranitramine – also known as octogen, a high explosive.

HWI – Hazardous Waste Incinerator – a destruction technique.

IM – Insensitive Munitions – Munition which reliably fulfils its performance, readiness and operational requirements on demand, but which minimizes the probability of inadvertent initiation and severity of subsequent collateral damage to the weapon platform, logistic systems and personnel when subjected to unplanned stimuli.

IMAS – International Mine Action Standards – A series of standards for humanitarian de-mining and destruction of anti-personnel mines.

JDTP – Joint Demilitarization Technology Program – US DoD programme for demilitarisation research.

London Convention – 1972 UN Convention on the Prevention of Marine Pollution by the Dumping of Wastes and Other Matter.

LP – Low Pressure.

MACT – Maximum Achievable Control Technology - a requirement that environmental legislation puts on pollution control and waste treatment.

MEC – Munitions and Explosives of Concern – US terminology for unexploded ordnance, discarded military munitions and munitions constituents present in high enough concentrations to pose an explosive hazard.

MEO – Mediated Electrochemical Oxidation – a destruction technique.

MIDAS – Munitions Items Disposition Action System.

MLRS – Multiple Launch Rocket System.

MMR – Military Munitions Rule.

MoD – Ministry of Defence.

MSO – Molten Salt Oxidation – a destruction technique.

NAMSA – NATO Maintenance and Supply Agency

NATO – North Atlantic Treaty Organization

Nature – A term for describing a particular munitions type.

NC – Nitrocellulose – cellulose nitrates used as a propellant.

NDIA – National Defense Industrial Association.

NEPM – National Environmental Protection Measure – Australian national environmental agreement.

NEQ – Net Explosive Quantity – a measure of the explosive quantity using TNT as a standard.

NG – Nitroglycerine – glycerol trinitrate, an explosive used in double base propellants.

NQ – Nitroguanadine – also known as picrite, an explosive used in triple base propellants.

NTO – 3-nitro-1,2,4-triazol-5-one – an insensitive high explosive.

OB/OD – Open Burning / Open Detonation – a destruction technique.

OBODM – Open Burning / Open Detonation Dispersion Model – a model for the atmospheric dispersion of emissions after OB/OD activities.

OECD – Organisation for Economic Cooperation and Development.

OSCE – Organisation for Security and Cooperation in Europe.

Oslo Convention/OSPAR Convention – The 1972 Convention for the Prevention of Marine Pollution by Dumping from Ships or Aircraft (Oslo) and the 1992 Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR)

PAD – Propellant Actuated Device – a small propellant loaded device extensively used in aviation. See also CAD.

PBX – Polymer Bonded Explosive – an explosive bound in a polymeric matrix, these present different demilitarisation challenges to meltcast and pressed explosives.

PCB – Polychlorinated biphenyls – organic pollutant previously used as an electrical insulator.

PCDD/F – Polychlorinated dibenzo-para-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) – more commonly dioxins and furans, organic pollutants produced by combustion of chlorinated products.

PCS – Pollution Control System.

Permitted List – An approach to regulation where all activities are considered to be banned unless they are explicitly permitted. Compare to black and grey lists.

Picric Acid – 2,4,6-trinitrophenol – formerly used explosive with commercial applications, including the dye industry.

Pink Water – Waste water from the loading, assembly and packing of munitions containing TNT, RDX or HMX as well as demilitarisation methods that involve water

POP – Persistent Organic Pollutants – organic pollutants such as dioxins, furans and PCBs.

Qualification – The assessment of an explosive material by the accredited authority to determine whether it possesses properties which make it safe and suitable for consideration for use in its intended role.

R^3 – Normally Resource Recovery and Reuse, however, can refer to any combination of waste related terms such as Reduce, Reuse, Recycle, Reclamation and Resource Recovery.

R^4 – Resource Recovery, Reuse and Recycling

RCRA – Resource Conservation and Recovery Act – US legislation which deals with waste and in particular hazardous waste.

RDX – Cyclo-1,3,5-trimethylene-2,4,6-trinitramine – also known as cyclonite or hexogen, a high explosive.

Red Water – Contaminated waste stream from the manufacture of TNT.

Retort – A chamber used for burning in an incinerator

RTO AVT – Research Technology Organisation – Applied Vehicles Technology

SAA – Small Arms Ammunition – generally rounds under 20mm in calibre.

SALW – Small Arms and Light Weapons – weapons such as pistols, rifles, sub-machine guns, machine guns, handheld grenade launchers, man-portable missile systems and mortars.

SCO or SCWO – Super Critical Water Oxidation.

SEESAC – South Eastern Europe Clearing House for the Control of Small Arms and Light Weapons.

STANAG – Standardisation Agreement

Stockholm Convention – 2001 Stockholm Convention on Persistent Organic Pollutants.

TATB – 1,3,5-triamino-2,4,6-trinitrobenzene – insensitive explosive, widely used in nuclear weapons programs.

TCDD – Tetrachlorinated dibenzo-para-dioxin, the most toxic dioxin and used as a standard for expressing dioxin and furan toxicity.

TEQ – Total Equivalency, a toxicity weighted measure of dioxin emissions where TCDD is given a weighting of 1.0.

TNT – 2,4,6-trinitrotoluene – a melt castable high explosive

Tritonal – TNT mixed with aluminium powder.

UXO – Unexploded Ordnance

VOC – Volatile Organic Compounds – organic chemicals with sufficiently high vapour pressures to vaporise under normal conditions.

WAO – Wet Air Oxidation – a destruction technique.

Wassenaar Agreement – Agreement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies

WID – Waste Incineration Directive (European Council Directive 2000/76/EC)

4. ENVIRONMENTAL IMPACT AND REGULATION

4.1 DUMPING

Historically, dumping was a common solution for disposal. This could be done in abandoned mine shafts, lakes or at sea depending on the availability of these sites. In the past, scientific opinion was that, particularly in a maritime environment, the explosive content of munitions would rapidly degrade and render them safe. The environmental impact of the dumping was largely ignored. Experience has shown that the degradation of explosives is such that dumped munitions pose a safety hazard for very long periods of time. The environmental impact of dumping can also no longer be ignored, munitions containing many materials that are potentially hazardous to the environment.

4.1.1 Sea Dumping

International measures to tackle indiscriminate sea dumping began with the 1972 UN Convention on the Human Environment in Stockholm which lead to the 1972 UN Convention on the Prevention of Marine Pollution by the Dumping of Wastes and Other Matter (London Convention).[5] This entered into force on 30 August 1975. The London Convention contained a 'black' list of banned wastes and a 'grey' list of wastes requiring special care but did not specifically ban sea dumping of munitions.

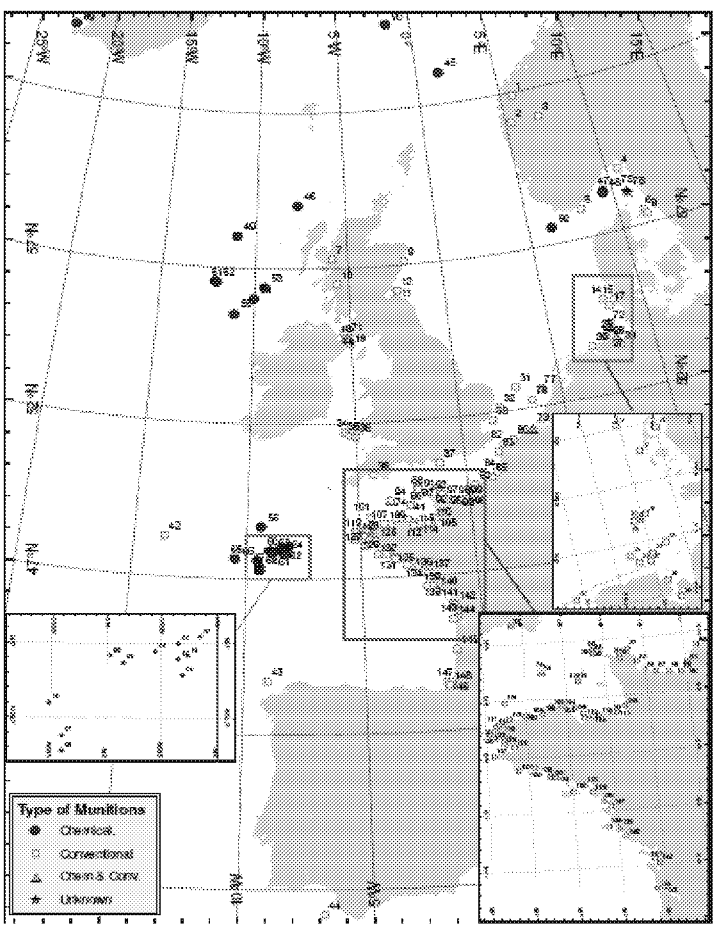

Figure 2– Location of Munitions Dumpsites within Western Europe

A series of regional conventions expanded on the work of the London Convention and further restricted sea dumping. For the UK, for example, the 1972 Convention for the Prevention of Marine Pollution by Dumping from Ships or Aircraft (Oslo Convention) which covered the North East Atlantic area required that dumping of munitions take place off the continental shelf. As a result a new dump site was located 400 nautical miles off Land's End. The map in Figure 1[6] shows the chemical and munitions dump sites in the Western Europe region. All sea dumping of munitions in the UK was ceased with the 1992 Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR or Oslo-Paris Convention).[7] The OSPAR Convention adopted a permitted list approach to sea dumping, therefore banning all sea dumping of waste that was not specifically permitted. The 1996 Protocol to the London

Convention adopted the permitted list approach which extends the ban on sea dumping of munitions worldwide. All MSIAC countries have ratified the London Convention (1972) and/or London Protocol (1996), see www.londonconvention.org.

4.1.2 Other Dumping

Dumping in internal waters such as lakes and land based dumping has been restricted by national legislation. Generally this requires specific landfills to be utilised and would restrict the disposal of hazardous items such as munitions. An example of this approach is found in the EU regulation. The Directive on the Landfill of Waste[8] provides that hazardous waste must only be disposed of in specific hazardous waste landfills and that liquid, flammable, explosive or oxidising waste may not be accepted in a landfill. These types of wastes would therefore require further treatment before landfill disposal.

4.1.3 Hazards from Dumpsites

Despite dumping being prohibited, previous dump sites continue to present hazards. In addition, old range or production sites can produce similar hazards. On the one hand there is a safety hazard associated with the discovery of Unexploded Ordnance (UXO), on the other hand the ordnance can cause environmental degradation even if undisturbed.

Dumped munitions that are not disturbed can be hazardous through leaching of toxins, with most explosives being toxic along with many other components of munitions. Leaching of toxic components can affect groundwater which may be used for human consumption. The toxins can also enter the human food chain. Self-ignition of munitions may also be a problem although the literature is inconclusive. The UK MoD commissioned the British Geological Survey to analyse seismic activity in the Beaufort's Dyke sea dumping area.[9] The survey identified 47 explosions in the dumping area of which at least 13 could be ascribed to military exercises and the like. Although potential self-ignitions in Beaufort's Dyke do not pose an immediate hazard, similar events in shallow water or on land would be of greater concern.

Where munitions are disturbed, for marine dump sites, the primary risk is through fishing which can result in the unintended recovery of UXO. Other activities such as dredging or offshore platform development can potentially infringe on marine dump sites. Imperial College London Consultants produced a literature review[10] of the hazards from sea dumping of munitions. For land sites, there is a risk of encroachment of development onto previously remote sites. In addition, items that were buried at a safe depth or areas that were cleared of UXO to a particular depth can become hazardous due to effects such as frost heave (also known as frost jacking), salt heave and erosion.

Frost heave is a well known phenomenon of soil displacement caused by expansion and contraction cycles due to seasonal frost. Although it is widely accepted that frost heave can cause buried munitions to migrate into shallower levels there is little published literature on the subject. From related literature on frost heave it is known that three conditions are necessary for frost heave to occur:[11]

- Temperature – freezing temperatures must penetrate the soil;
- Soil – must be frost-susceptible which usually means small particle sizes (below 0.05 mm) such as silt; and
- Water – must be available in the affected area.

In 2003-2004, the US Army conducted a study into frost heave.[12] They found that the ordnance shapes were raised during soil expansion to roughly the same extent as the soil but did not subside to the same degree during contraction. There was variation in the effect depending on the type of ordnance shape. The 2.75 inch rocket and 81 mm mortar shapes on average moved upwards four times as far as smaller 20 mm and 40 mm projectiles. The 155 mm ordnance shapes did not move which was ascribed to the greater weight counteracting the effect of heave.[13]

4.2 THERMAL DISPOSAL – IMPACT AND REGULATION

4.2.1 Modes of Impact

Thermal treatment includes both Open Burning and Open Detonation (OB/OD) and incineration. Although the actual emissions and the degree of control available vary between these techniques, the modes of environmental impact are similar. Looking at incineration: according to the European Integrated Pollution Prevention and Control Bureau (EIPPC) Reference Document[14] the direct environmental impacts from incineration include:

- process emission to air and water (including odour);
- process residue production;
- process noise and vibration;
- energy consumption and production;

The air emissions fall into a number of categories posing environmental risk:

- particulate matter;
- acidic gases – in particular hydrogen chloride, sulphur dioxide and nitrous oxides;
- toxic metals – including arsenic, beryllium, cadmium, chromium, lead, mercury and nickel; and
- carbon compounds – including carbon monoxide, hydrocarbons (volatile organic compounds or VOC), dioxins and furans (PCDD/F) and polychlorinated biphenyls (PCBs).

All of these substances have been the subject of regulation, largely at a national level or within the EU. One exception is the 2001 Stockholm Convention on Persistent Organic Pollutants (POPs)[15] which governs dioxins, furans and PCBs amongst other pollutants. Details of emission limits are described in section 4.2.3 on incineration and control measure for air emissions are described in section 6.5.5.

Emissions to water can occur through effluent discharge following waste water treatment or through leaching from contaminated sites. These issues are not specific to thermal disposal. Waste water treatment is an issue for any process where explosives and water come into contact. This is most serious in other industrial demilitarisation process such as water washout and oxidation treatments and is discussed in section 4.3.

Process residues include:

- residual ashes, slag or scrap following thermal treatment,
- residues and dust from pollution control systems, and
- sludge from waste water treatment.

The disposal of process residues will depend on whether they are hazardous. For residues being disposed of in landfill or recycled into civil engineering applications the key characteristic is leachability. Leaching, in this context, is the process by hazardous material is dissolved in groundwater and hence contamination of groundwater occurs from solid waste.

Noise is a particularly issue for open detonation although open burning and incineration will generate noise comparable to other industrial processes. Noise propagation is heavily dependent on atmospheric conditions and depending on the siting of a facility with respect to populated areas it may be necessary to limit open detonation activities to particular days with suitable weather conditions.

Almost all thermal treatment will entail some energy consumption. Although some propellant open burning or explosives open detonation applications might utilise the munitions ignition or detonation system, usually some form of donor charge or igniter will be used. To ensure near to complete destruction a significant charge will be required. Incineration systems will utilise some form of fuel for the burner. Waste heat recovery through steam powered electricity generation may, to some degree, compensate for this.

The representative environmental hazards from industrial demilitarisation, whether thermal or other means, are shown in Figure 3. Note that all of these hazards and impacts can be minimised or eliminated through proper management and regulation.

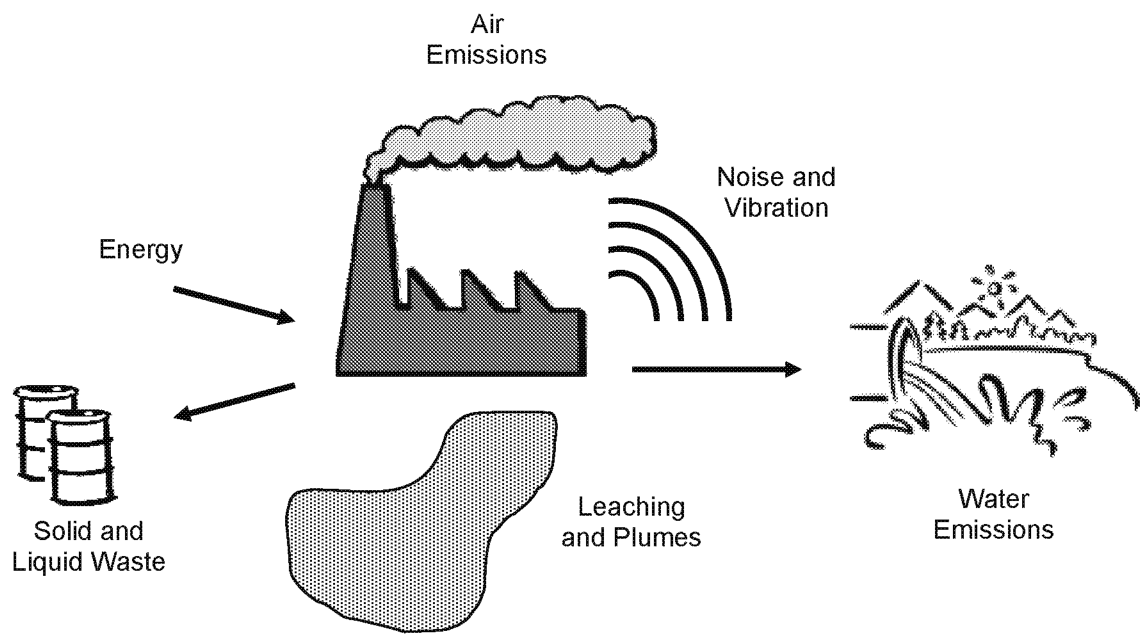

Figure 3 – Representative Environmental Hazards from Industrial Demilitarisation

4.2.2 <u>Open Burning and Open Detonation</u>

Open burning and open detonation (OB/OD) has, particularly since the banning of dumping, been an expedient means of disposal of munitions. In common with the open burning of other waste, this practice is under increasing scrutiny. Open burning of general waste is restricted around the world as the low temperatures and uneven combustion of uncontrolled burning tends to generate a considerably greater mass of hazardous emissions such as dioxins than incineration. Although incineration is subject to intense criticism from environmental organisations such as Greenpeace, there is widespread agreement that open burning of general waste has a greater environmental impact. However, unlike general waste, munitions have a well characterised and limited set of constituents and munitions are burnt or detonated when used for their intended purpose.

Regulation of OB/OD is generally concerned with safety and security. A number of countries, notably Germany, the Netherlands and Canada have banned OB/OD although in Canada's case this only applies to the military destruction of SAA and manufacturers are still able to use open burning to destroy production wastes. The NATO Maintenance and Supply Agency (NAMSA) actively prohibits the use of OB/OD in most demilitarisation contracts.[16]

4.2.2.1 Emissions Database

Although air emissions from OB/OD are necessarily uncontrolled, efforts have been undertaken to characterise them. Studies of the products of explosive decomposition of bare explosives do not take into account the contribution of non-energetic components of the munition and the entrainment of dirt to the emissions. As a result, trials of OB/OD activities need to be used.

Dr. Bill Mitchell authored a review for the South Eastern Europe Clearinghouse for the Control of Small Arms and Light Weapons (SEESAC)[17] which gives a good history of the most extensive database of OB/OD data. The US EPA developed an emissions database based on US DoD trials, largely in inflatable detonation chambers known as 'Bang Box' tests. This emissions database was used to assist environmental assessments for OB/OD activities at US military sites. The US Army Defence Ammunition Center (DAC) and Chemical Compliance Systems Inc. extended this database by including further test results and information on energetic compositions. The updated database also moved from a system based on Emissions Factors related to the Net Explosive Quantity (NEQ) to a system based on Environmental Fate Factors (EFF) related to the actual composition of the munition. In this way the results could be tailored to the particular natures being destroyed.

Dr. Mitchell's work for SEESAC and the UN Development Programme (UNDP) further adapted the emissions database to make it more suitable for environmental impact assessment. Amongst other measures, this involved removal of substances without harmful health effects and more sophisticated handling of non-detect values. The resulting UNDP OB/OD Emissions Database (EDB) was included as an annex to the SEESAC paper. The paper includes examples illustrating that OB/OD of particular ammunition natures meets incineration air emission standards. A number of assumptions are made in this analysis in order to compare two fundamentally different processes and the paper contains a number of caveats. One caveat missing is that the estimated OB/OD emissions are being compared to the incineration limits and not to actual incineration emissions which may be significantly less than the limits.

In the US, although not banned, OB/OD activities are subject to permits. At Naval Air Weapons Center (NAWC) China Lake extensive work was done to provide more realistic permitting for OD operations.[18] China Lake deals with large quantities of non-standard munitions in its R&D role. Due to this, industrial demilitarisation is difficult option and OD is used almost exclusively. China Lake is an excellent site for OD with an large, remote and arid site with the groundwater table more than 400 feet (122m) below, however operations were restricted by a conservative risk assessment and in particular the need to unpack waste. They had three main areas of effort:

- Using the existing emissions database they applied a system of discarding compounds of low health risk and using surrogate compounds to improve areas where data was unavailable and worst-case scenarios would normally be adopted.
- They undertook studies to show that the majority of metal in casings fragments rather than vaporises and therefore should not be included in emissions.
- They conducted small scale testing that showed that the formation of dioxins from OD of explosives contaminated wastes was orders of magnitude less than the original hazard risk assessment based on a medical waste incinerator.

4.2.2.2 Dispersion Models

A key area which requires additional modelling to accurately assess the environmental impact is the dispersion of emission plumes. A number of models could be used for this, some examples are:

- US Army Open Burn/Open Detonation Dispersion Model (OBODM)[19] developed at Dugway Proving Ground. This is listed as an alternative model by and is freely available from the US EPA.
- Atmospheric Dispersion Of Reactive Agents (ADORA) developed by BlazeTech Corporation.
- [20] This is a commercial product originally developed for the US Air Force.
- Strategic Environmental Research and Development Programme Compliance Project CP-1159 under development by Aerodyne Research Inc.

4.2.2.3 Site Characterisation

The effect of contamination of soil and groundwater would also need to be considered. Defence Research Establishment Valcartier (DREV) (now Defence Research and Development Canada – Valcartier) conducted a programme of site characterisation including a number of OB/OD sites. This work is summarised in the Canadian Department of National Defence review by Rodrigue Boulay of Canadian demilitarisation activities.[21] DREV's work included the study of an OD site at CFAD Dundurn,[22] a SAA burning site at the same base,[23] an OB/OD site at CFAD Bedford[24] and propellant burning, white phosphorous burning and OD sites at CFAD Rocky Point.[25] The characterisation of the sites focussed on soil and groundwater contamination by energetic materials with the exception of the SAA disposal site at CFAD Dundurn which looked t heavy metal contamination. None of the surveys considered air pollution. In summary, the results were:

- Low or undetectable levels of contamination at the OD sites at CFAD Dundurn and Bedford.
- High levels of nitroglycerine contamination at CFAD Rocky Point where propellant burning was conducted on grass. They noted that the combustion was frequently incomplete.
- 'Quite severe' local heavy metal contamination at the SAA site at CFAD Dundurn and moderate lead contamination at CFAD Rocky Point.
- At all sites there was either no groundwater contamination or the groundwater flow was such that there was no risk to human health.

The conclusions reached from the Canadian studies were that OD is cleaner than OB and that care must be taken to ensure that OB is conducted on burning pads and complete combustion is ensured. Due to the lead content, SAA should not be disposed of by OB.

Although groundwater contamination was limited, they recommended continued monitoring. Dubé et al.[26] looked reviewed the Canadian blow-in-place (ie. OD) procedures with respect to their environmental impacts. This emphasised the importance of ensuring high-order detonations.

The Finnish Defence Force looked at the environmental impact at a site destroying about 500 tons per year of obsolete propellant by open burning.[27] They found evidence of localised contamination but concluded that with the continued use of a burning basin and treatment of residues that OB would not be harmful. It should be noted that the soil type at the burn site would restrict penetration of organic pollutants. A matching Finnish study of their OD site at Hukkakero in Lapland[28] found that although there was some localised TNT contamination and some heavy metals contamination restricted to a three kilometre radius of the site. They concluded that the environmental impact was acceptable.

Most munitions requiring disposal are obsolete and therefore are likely to have simple energetic fillings. Increasingly in the future, however, munitions with more sophisticated fillings designed to improve Insensitive Munitions (IM) characteristics will be common in demilitarisation activities. By their nature, IM are designed to react less violently to thermal effects so this is likely to have major impact on OB/OD. No published reports were found that looked at the level of energetic material residue from OB/OD of IM compared to conventional munitions.

4.2.3 Incineration

4.2.3.1 Air Emissions

The primary focus of incineration regulation is air emissions. Both the US and the EU have recent, prescriptive regulations air emissions during the incineration of waste. The EU Waste Incineration Directive (2000/76/EC),[29] which has also been implemented in Canada replaces a raft of previous regulation and sets a single common standard across incinerators recognising that the significant factor is not the material incinerated but the emissions. The equivalent US regulations are the Standards for Hazardous Waste Incinerators (40CFR63.1200).[30] Australian jurisdictions do not have an equivalent regulation prescribing emission standards; however, State EPAs would normally require applications for incineration permits to comply with the EU standard.

The regulations are broadly similar. Both make distinctions between new and existing incineration plants or permits. The EU regulation differs in having a series of sunset clauses; the directive applies to new incinerators from 28 December 2002, existing incinerators from 28 December 2005 and different limits, namely double metal emissions and no NO_x limit, apply to existing hazardous waste incinerators until 01 January 2007.

Significant differences occur in a number of areas:

- Destruction efficiency – US regulations set a minimum destruction efficiency, no such requirement exists in the EU regulations;
- Categorisation of metal emissions – the US regulations define different limits for Low Volatility Metals (LVM) and High Volatility Metals (HVM), the EU regulations divide metals into two categories and cover a wider range of toxic metals but the division is different; and
- NO_x and SO_2 – Only the EU regulations provide limits for these.

The relevant emission levels are shown in Table 1 for comparison. It should be remembered that differences in the detail of measuring techniques means that, although indicative, this is not necessarily a direct comparison.

Table 1 – Comparison of EU and US Regulations for Incineration[31]

Emission Level or Requirement	2000/76/EC All	40CFR63.1200 Existing	New
Destruction and removal efficiency (%)	-	99.99	
Particulate Matter (mg m^{-3})	10	34	34
Sulphur dioxide (mg m^{-3})	50	-	
Hydrogen fluoride (mg m^{-3})	10	-	
Hydrogen chloride (mg m^{-3})	10	114.8 (77 ppm)	31.3 (21 ppm)
NO_x expressed as Nitrogen dioxide (mg m^{-3})	200	-	-
Carbon monoxide (mg m^{-3})	50	114.6 (100 ppm)	
Cd and Tl (µg m^{-3})	50	-	-
Mercury (µg m^{-3})	50	130	45
Other toxic metals (µg m^{-3}) Sb, As, Pb, Cr, Co, Cu, Mn, Ni and V	500	- -	
Low Volatility Metals (Pb and Cd) (µg m^{-3})	-	240	120
High Volatility Metals (As, Be and Cr) (µg m^{-3})	-	97	
Dioxins and furans expressed as total equivalence (ng m^{-3})	0.10	0.20	

Notes on Table 1:

- EU limits are the final values for all incinerators after 01 January 2007.
- All values are for 7% oxygen except for EU particulate matter limit at 11% oxygen.
- Total equivalence (TEQ) is the sum of dioxins and furans (PCDD/PCDF) expressed as TCDD with respect to relative toxicity.

4.2.3.2 Other Requirements

The EU regulation has a number of other elements relevant to explosive waste incineration. It covers co-incineration plants but does not cover experimental plants or plants treating less than 50 tonnes of waste per year. The heat generated must, as far as possible, be put to good use. Most significant are the temperature requirements. These are designed to ensure destruction of Volatile Organic Compounds (VOC) and suppress dioxin formation. The requirements are that the incinerator must operate in excess of:

- 850ºC with a gas residence time of 2 seconds for all incinerators; and
- 1100ºC for 2 seconds for hazardous waste with more than 1% halogenated organic substances expressed as chlorine to reduce dioxin emissions.

The UK Department for the Environment, Food and Rural Affairs (DEFRA) publishes guidance on the WID[32]

Incineration, even with stringent emissions limits, is a controversial subject. For example, Greenpeace campaigns against the use of waste incineration and publishes reviews into the health hazards of incineration.[33] Some groups see the OSPAR convention as mandating a zero hazardous emissions regime by 2020. This, they claim, would rule out incineration as a waste treatment option.

From 1976, the London Convention (see Section 4.1) adopted resolutions controlling or restricting incineration at sea. In the 1996 Protocol, incineration at sea was completely banned although previous agreement had seen the practice ceased in 1991.

4.3 OTHER INDUSTRIAL TREATMENTS

The environmental impact of industrial demilitarisation techniques varies from technology to technology however the modes of impact are similar and in fact are similar to those found in munitions manufacturing. Regulations for waste water emissions and solid waste disposal are national or even state specific.

The major potential environmental hazards are:

- TNT, RDX and HMX contaminated waste water, referred to as pink water,
- Nitrate contaminated waste water,
- Perchlorate contaminated waste water,
- Residual energetic material,
- Contaminated solid waste,
- Contaminated process consumables, and
- Hazardous chemicals used in processing, in particular solvents and acids.

These contaminants do not pose a hazard if properly contained and treated however if they are allowed to enter the environment they can pose a risk to human health. The primary concern is normally leaching of the contaminant into the groundwater system where it can be transported to wells used for human consumption in the form of a plume or can enter the human food chain. Other health hazards can arise through exposure of employees or of the general public if contaminated land is utilised for different roles.

The science of waste water contamination is the subject of a vast body of literature and regular conferences but it is beyond the scope of this report. It is illustrative however to look at the most common waste stream generated from demilitarisation and also the most common form of treatment.

4.3.1 Treatment of Pink Water

Pink water does not have a particular composition. It can contain TNT, RDX, HMX or the by-products of these explosives such as DNT. The name comes from the characteristic colour that the initially clear waste water takes on exposure to light. Pink water comes from the loading, assembly and packing of munitions as well as demilitarisation methods that involve water. In contrast, red water is a contaminated waste stream specifically from the manufacture and purification of TNT.

The discharge of pink water into the environment is strictly controlled in most jurisdictions. To treat waste water to meet these requirements Granulated Activated Carbon (GAC) is most commonly used. GAC consists of carbon based material such as charcoal which is treated to provide a very high surface area (in excess of 500 m^2g^{-1}) and hence very high absorption characteristics. This allows GAC to absorb nitrogen based compounds very effectively. After treating pink water, the GAC is a hazardous waste and must be treated, normally by incineration. A GAC treatment facility is illustrated in Figure 4.

Although not strictly a demilitarisation effluent, red water is normally treated by incineration. This yields a sodium sulphate rich ash that can potentially be disposed of by landfill.[34]

Figure 4 – GAC Columns for RDX Waste Water Treatment at ADI Mulwala

5. TRANSPORT REGULATION

The regulation of the transport of material in demilitarisation activities can essentially fall under two regimes: dangerous goods or hazardous waste. If the material is regarded as dangerous goods then its transportation will be undertaken in accordance with national legislation based on the UN Model Regulations (The Orange Book).[35] If the material is classified as hazardous waste then the transportation will be governed by the EPA or equivalent in each nation. This will generally mean that the transportation and storage will be subject to additional regulation and permit requirements.

5.1 MILITARY MUNITIONS RULE (USA)

The US resolved this issue with the EPA Military Munitions Rule (MMR).[36] With the Final Rule issued in 1997, the US EPA granted the US DoD an exemption from a number of elements of the Resource Conservation and Recovery Act (RCRA). For the purposes of defining solid waste, the MMR states that an unused munition is solid waste only when it is:

- abandoned by being disposed of, burned, or incinerated, or treated prior to disposal;
- removed from storage for the purposes of disposal or treatment prior to disposal;
- deteriorated, leaking, or damaged to the point it can no longer be put back into serviceable condition, and cannot be reasonably recycled or used for other purposes; or
- determined by an authorised military official to be solid waste.

This has the important effect that, provided they are serviceable, munitions in the disposal account or otherwise obsolete are not considered waste until they are actually demilitarised. Additionally, the MMR conditionally exempts waste munitions that are transported or stored in accordance with DoD military munition shipping and storage controls and standards from RCRA manifest, container marking and storage regulations. This reflects that military munitions are already tightly and effectively regulated by the DoD.

The MMR does not, however, provide any exemption to the process of demilitarisation. This is made clear in the Response to Comments[37] that, although storage and transportation may potentially be exempt, the treatment of the waste would not be. This means that there is no difference in the regulation applied to government agencies, government contractors and other companies in terms of demilitarisation.

The MMR also defines that military munitions used for their intended purpose are not solid waste. This includes use in training, research, development, test and evaluation as well as destruction during range clearance operations. However, used munitions are solid waste if they are moved from their landing spot and managed off-range or disposed of on-range. This prevents the situation where expended munitions being left in place on an active range could potentially contravene requirement of waste management.

Other nations have not yet followed the US approach of defining when munition are defined as waste. As the definition of waste in EU regulation is quite broad, it is possible that obsolete munitions or expended munitions could be very easily considered hazardous waste with corresponding regulatory obligations.

5.2 INTERNATIONAL TRANSPORT

5.2.1 Basel Convention

The 1989 Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention)[38] sought to restrict the export of hazardous waste, in particular from developed countries to developing countries. The convention requires written notification for specified classes of waste (essentially hazardous wastes) for their export to other countries or transboundary movements. The Ban Amendment was adopted by the Basel Convention on 22 September 1995 to impose even stricter controls on the export of hazardous waste. This has not yet entered into force. The Ban Amendment's key change is to ban the export of hazardous waste from 'Annex VII' states (the OECD, EU and Liechtenstein) to non-Annex VII states (ie. developing countries). Although the Ban Amendment has not entered into force, a number of regional agreements such as the Bamako and Waigani Conventions banning import of hazardous waste into Africa and the South Pacific respectively have been ratified. Most significantly, EU regulation gives effect to the Ban Amendment.

5.2.2 EU Regulation

The EU regulations enacting the Basel Convention are Council Regulation (EEC) No. 259/93[39] subsequently amended to enact the Ban Amendment[40] and the proposed replacement regulation.[41] The proposed regulation will ban the shipment of hazardous waste from EU countries other than EFTA, OECD countries or Liechtenstein. Other relevant sections of the regulation are the requirements to certify disposal or recovery of the waste either 180 days for the existing regulation or one calendar year for the proposed regulation. The regulations require written notification of the shipments to destination and transit countries with the proposed regulation requiring a written approval and thus removing the facility for tacit consent.

The EU regulations do not currently apply to munitions being transported for demilitarisation in Europe with the reported exception of Sweden. In common with the US, military munitions are regarded as already regulated more tightly than hazardous waste. Unlike the US, there is no Munitions Rule to make this understanding explicit. The Waste List[42] defines classes of waste under which section 16 04 is Waste Explosives containing subsections 01 Waste Ammunition, 02 Fireworks Waste and 03 Other Waste Explosives; all of which are considered hazardous waste. A listing in the Waste List does not necessarily mean that a substance is a waste in all circumstances. For example, the definition from the Framework Waste Directive[43] of waste would need to apply:

> *"waste" means any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force*
> *"disposal" means:- the collection, sorting, transport and treatment of waste as well as its storage and tipping above or under ground [and]*
> *- the transformation operations necessary for its re-use, recovery or recycling.*

Although military munitions are not generally considered as waste due to their tight national controls the waste products of a demilitarisation process could potentially be hazardous waste and this might affect, for example, the transport of explosive contaminated slurry for incineration at another facility.

The implications of the EU regulations are widely misunderstood and even if applied to munitions would not necessarily prevent their export for demilitarisation. They would require additional effort in meeting hazardous waste markings for transportation and in applying for the necessary approvals for transboundary shipment. Since the countries with a significant capacity for industrial demilitarisation are all "Annex VII" states there is no ban on export. Export would be subject to approval by the importing country and it is possible that the environmental agencies of a particular country might seek to block the import of munitions for disposal. This could particularly be a risk if public perception of demilitarisation was negative and put pressure on national governments.

5.3 INTERSTATE TRANSPORT

Countries such as Australia and the United States have federal systems where the states retain significant constitutional powers. These would not generally apply to military munitions however it is illustrative to consider what the implications of treating munitions destined for demilitarisation as hazardous waste would have on interstate transport of munitions.

5.3.1 Australia

In Australia, the National Environment Protection Measure (NEPM) on Movement of Controlled Waste[44] sets analogous requirements to the Basel Convention. It requires prior notification of a shipment and authorisation from the appropriate authorities in the destination state. Although an additional level of regulation, this would not necessarily prevent interstate movement of munitions for demilitarisation. Significantly, there is scope for exemption for cases when logistical reasons entail transit through another jurisdiction prior to return the original jurisdiction as could be the case for a facility located near state borders.

5.3.2 United States

In general terms, the States in the US are limited in their power to regulate interstate hazardous waste shipment as it is governed by the Commerce Clause of the US Constitution.[45] This empowers the US Congress to regulate interstate commerce. Through the Resource Conservation and Recovery Act (RCRA), the US EPA is responsible for regulating interstate hazardous waste transportation. Although the States can legislate on the matter, they cannot unduly restrict interstate commerce and therefore a system of approval analogous to the Basel Convention is not possible. Due to the Military Munitions Rule, this does not affect the transport of waste munitions for demilitarisation.

6. DEMILITARISATION AND DISPOSAL TECHNIQUES

6.1 STANDARDS

The only current international standard for demilitarisation is the NATO STANAG 4518.[46] This document provides a brief overview of the demilitarisation process and of some of the techniques available. It also provides some design safety principles that will assist in the demilitarisation of munitions and an example demilitarisation plan. The information included is brief and generally falls short of providing a true guide for demilitarisation of munitions. Unfortunately, a more detailed document that could complement the top-level STANAG does not yet exist. The NATO Ammunition Safety Group (AC/326) Subgroup 5 deals with Logistic Storage and Disposal of munitions and may develop guidance, possibly for inclusion in the NATO Manual on Safety Principles for the Storage of Ammunition and Explosive (AASTP-1).

Although the Organisation for Security and Cooperation in Europe (OSCE) has some guidance on the destruction of Small Arms and Light Weapons (SALW), the only other international guidance is provided by the United Nations Mine Action Services organisation. The International Mine Action Standard (IMAS) 11.10[47] deals with the destruction of stockpile anti-personnel mines which is essentially a demilitarisation task. It contains brief guidance on relevant environmental and transport regulation, considerations in demilitarisation and annexes on a variety of techniques. It is focussed on the demilitarisation of anti-personnel landmines and is therefore limited in its application to general demilitarisation.

For given methods of demilitarisation, in particular Open Burning and Open Detonation (OB/OD), national standards exist. These will be discussed under in the relevant section for that technique.

6.2 REVIEWS

A review of the literature on individual demilitarisation techniques occupies the majority of this section, however, a number of reviews have been published covering a range of techniques, either to assess different methods or to provide an overview of research. These are discussed first.

Demilitarisation research in the US is coordinated under the Joint Demilitarization Technology Programme (JDTP) which is managed by the Defence Ammunition Center (DAC) at McAlester in Oklahoma and an overview of the programme is given in the October 2003 report to Congress.[48] Within the JDTP, majority of research is managed by the Naval Surface Warfare Center Crane Division, Indiana for the US Navy and Armament Research, Development and Engineering Center (ARDEC) at Picatinny Arsenal, New Jersey for the US Army. Both of these organisations regularly provide reviews of the progress in the research programmes that they manage. Recent examples of these reviews are found in Burch et al. for Crane[49] and Goldstein for ARDEC.[50]

A considerable amount of interest in advanced demilitarisation techniques has been generated by the need to destroy chemical weapon stockpiles in accordance with the Chemical Weapons Convention. While developing an incineration based baseline destruction process, the US investigated alternative technologies which were published in a 1993 review under the auspices of the National Research Council.[51] In the face of public opposition to incineration a further review was conducted and published in 1999[52] and subsequent more limited reviews and updates have been published. Although focussed on chemical weapons destruction, many of the techniques reviewed have application to conventional weapons as well.

Naval Air Warfare Center Weapons Division reviewed demilitarisation techniques for the Naval Air China Lake Base in California.[53] China Lake is a research and development facility so the energetic materials to be destroyed are varied and not suited to many techniques. As a result only a limited number of techniques were studied in detail. Nevertheless, the categorisation of techniques is useful and a similar method has been adopted for this review. The report found that no technique offered clear advantages over OD, however, it must be noted that China Lake has a particularly good OD site and an unusual waste stream.

Within Europe, the Western European Armaments Organisation (WEAO) commissioned a study of demilitarisation techniques through the Common European Priority Area (CEPA) 14.6. The study was conducted by the then RO Defence (now BAe Land Systems) and the Danish Contractor DEMEX in 1999 and 2000. The study focussed on advanced conventional munitions as opposed to the more normal approach of focussing on obsolete munitions that currently occupy the demilitarisation stockpile. Some of the conclusions of the CEPA 14.6 reports were presented by Stalker[54] and Lauritzen et al.[55]

Although not strictly a review, the US Munitions Items Disposition Action System (MIDAS) is a useful source of demilitarisation information. MIDAS was developed by the Defence Ammunition Center (DAC) and is a web based database of detailed munitions information. Amongst the information are disposition alternatives that list existing and emerging demilitarisation techniques that may be applicable to a particular munitions nature.[56]

6.3 OVERVIEW

A matrix of the current techniques in demilitarisation is given in Table 2. This gives a brief description of the techniques described in this section, their usage and maturity and also some notes on their advantages and disadvantages. The techniques are categorised by the stage of the demilitarisation process that they apply to. These are:

- Disassembly and pre-treatment – techniques providing access to the energetic material or size reduction prior to further treatment. Disassembly could also involve sending different munition components for different demilitarisation processes;
- Removal – techniques for removing energetic material from munitions;
- Destruction – techniques for destroying energetic material or converting it to less toxic and energetic products; and
- Resource Recovery and Recycling – techniques particularly related to Resource Recovery and Recycling.

In the remainder of section 6 the same categorisation is used however the disassembly and removal processes are combined as some related techniques can be applied to either process and are best described together.

InTable 2, the usage column gives some indication of the types of munitions or waste streams that can be treated with this process. Secondary waste streams in this column should be taken to mean the waste streams of processes such as alkaline hydrolysis that have removed the explosive properties of the waste but require further treatment

Maturity refers to the usage in a demilitarisation context, therefore a technique may be common in another industrial context but still at a research or prototype level in demilitarisation. In particular, the phrases in this column indicate:

- 'Widespread use' identifies those techniques which are the most common forms of demilitarisation;
- 'In use' identifies other techniques which are in use for demilitarisation beyond pilot plants;
- 'Available' identifies techniques which have progressed past prototyping to be commercially available but where it is not known if they have been applied to demilitarisation;
- 'Prototype' identifies techniques which are in a prototype or pilot phase. Some pilot plants may process considerable volumes of munitions;
- 'Research' identifies techniques which are believed to have not progressed past

Table 2 - Matrix of Demilitarisation Techniques

Technique	Description	Usage	Maturity	Notes
Disassembly and Pre-treatment				
Disassembly, Manual	Disassembly, punching, crushing or cutting by manual means	All natures	Widespread use	Flexible – easy to adapt to different munitions Low setup costs Safety issues associated with manual disassembly of munition
Disassembly, Robotic	Disassembly, punching, crushing or cutting remotely	All natures	Widespread use	Reduces personnel exposure to munitions Less flexible than manual disassembly
Cutting, Abrasive Water or Slurry Jet	Sectioning by a high pressure abrasive water or slurry jet	All natures	In use	Flexible and quick Generates waste water Useful with UXO and MEC
Cryofracture	Liquid nitrogen bath embrittles munitions before mechanical pressing	Small detonable items	Widespread use	Ensures no high order event during incineration An additional process that may not be necessary
Cryocycling	Liquid nitrogen bath rubbilises propellant	Rocket motors	Available	No waste water Does not affect material properties of propellant An additional process that may not be necessary
Ultrasonic	Ultrasonic pulses induce cavitation in a salt bath to fragment explosives	Meltcast explosives	Research	Potentially cost effective and environmentally friendly
Removal				
Machining, Mechanical	Dry machining of energetic materials by contour drilling	All natures except small munitions	In use	No waste water Typically only removes 95% of explosive so further treatment is necessary
Washout, HP Water	Ablation of energetic material by a high pressure water jet	All natures except small munitions	Widespread use	Moderate pressures Generates waste water Difficult with small munitions
Washout, Liquid Nitrogen	Ablation of energetic material by a high pressure liquid nitrogen jet	All natures except small munitions	Available	No waste water Complexity of cryogenic storage

Technique	Description	Usage	Maturity	Notes
Washout, Ammonia	Ablation of energetic material by high pressure ammonia jet	All natures except small munitions	Research	Ammonia is a solvent and desensitiser for wide range of explosives
Blastout, Carbon Dioxide	Ablation of energetic material by high velocity carbon dioxide particles	Pressed explosives	Prototype	No waste water As an adjunct to machining to avoid thermal treatment of residues
Meltout, Steam	Meltout of explosive by steam or hot water jets	Meltcast explosives	Widespread use	Generates waste water Moderate temperature and pressures
Meltout, Autoclave	Meltout of explosive by hot water in a pressurised vessel	Meltcast explosives	Widespread use	Reduced waste water generation Moderate temperature and pressure
Meltout, Microwave	Meltout of explosive by microwaves	Meltcast explosives	Prototype	No waste water Care needs to be taken to ensure safety
Meltout, Induction	Meltout of explosive by induced current in case	Meltcast explosives	Prototype	No waste water Care needs to be taken to ensure safety
Machining, Laser	Laser ablates energetic material	Explosives	Research	No waste water Precise machining Care needs to be taken to ensure safety
Destruction				
Open Burning	Uncontained burning	Non-detonable items and waste	Widespread use	Simple process that does not require industrial plant Potential environmental impact
Open Detonation	Uncontained detonation using a donor charge	Detonable items and waste	Widespread use	Simple process that does not require industrial plant Potential environmental impact
Contained Detonation	Detonation by a donor charge in a contained chamber	Small detonable items	In use	Pollution control Transportable Small capacity batch process
Contained Burn	Ignition of rocket motors in a contained chamber	Rocket motors	Prototype	Pollution control Small capacity batch process No additional fuel required
Incineration, Static Kiln	Incineration in a sealed chamber. Items can burn or detonate	All natures expect large detonable items after pre-treatment	In use	Pollution control Small capacity batch process Items may require pre-treatment such as sectioning before incineration

Technique	Description	Usage	Maturity	Notes
Incineration, Rotary Kiln	Incineration with the items slowly moved through the kiln	Non-detonable items and small detonable items	Widespread use	Pollution control Items may require pre-treatment such as sectioning before incineration
Incineration, Car Bottom Furnace	Incineration using a moveable 'car' to insert the waste	Explosive contaminated waste	Widespread use	May have pollution control Can handle unusual shapes Small capacity batch process
Incineration, Plasma Arc	Molten slag is heated by a plasma arc and destroys munitions	All natures except large detonable items	In use	Can deal with pyrotechnics Slag encapsulates hazardous waste Items may require pre-treatment such as sectioning before incineration Relatively expensive for bulk energetics
Incineration, Fluidised Bed	Incineration where the waste slurry is fluidised by air jets to improve combustion	Explosive waste slurry or granular solids	Available	Reduced acid gas production Efficient conversion to energy
Molten Metal Pyrolysis	Decomposition by molten metal slag	Not known	Research	Effective destruction of toxic components Expensive due to high temperatures
Oxidation, Alkaline Hydrolysis	Oxidation at moderate temperatures and pressures with a strong alkali	Explosive waste slurry or granular solids	Prototype	Waste feed may still be toxic
Oxidation, Actodemil	Oxidation at moderate temperatures and atmospheric pressure with a potassium hydroxide/humic acid reagent	Explosive waste slurry or granular solids	In use	Waste feed can be used directly as fertiliser
Oxidation, Supercritical Water	Oxidation at supercritical conditions (374ºC and 22.1 MPa) using water	Secondary waste stream	Prototype	Effective destruction of toxic components Very extreme reaction conditions Issue with buildup of inorganic salts
Oxidation, Molten Salt	Oxidation with liquid carbonate salt bath	Explosive waste slurry or granular solids	Prototype	Lower operating temperature than incineration Environmentally friendly due to low acidic gas generation and the trapping of inorganic components in salt bath

Technique	Description	Usage	Maturity	Notes
Oxidation, Mediated Electrochemical	Oxidation by a metal ions in a electrochemical cell	Explosive waste slurry	Prototype	Complicated and expensive for bulk treatment Possible application for primary explosives
Oxidation, Wet Air	Oxidation by oxygen at elevated temperatures and pressures (up to 320°C and 22 MPa)	Secondary waste stream	Available	More benign reaction conditions than supercritical water Commercially available but prototype stage only for demilitarisation
Oxidation, Direct Chemical	Oxidation by perodydisulphate at moderate temperatures and pressures	Explosive waste slurry or granular solids	Research	Powerful oxidiser that requires appropriate safety
Oxidation, Adams Sulphur	Oxidation by elemental sulphur at elevated temperatures and atmospheric pressure	Explosive waste slurry or granular solids	Research	Air emissions require treatment but residues are easy to dispose of Unsuitable for large quantities of waste water
Oxidation, Photocatyltic	Oxidation by UV light or by visible light with a catalyst	Secondary waste stream	Research	Potentially high operating costs
Biodegradation, Aqueous/Slurry	Biodegradation by microbes in a bioreactor	Explosive waste slurry or secondary waste stream	In use	In use for perchlorate treatment Cheap and environmentally friendly option
Biodegradation, Enzyme	Biodegradation using enzyme catalysts	Explosive waste slurry or granular solids	Research	Potential to improve biodegradation of TNT Unknown end-products
Biodegradation, GAC-FBR	Biodegradation using Granular Activated Carbon and a Fluidised Bed Reactor	Explosive waste streams	Prototype	Potentially cheaper than GAC for treatment of pink water
Resource Recovery and Recycling				
Resale	Sale of munitions to foreign governments	Serviceable munitions	In use	Limited by arms proliferation agreements Munitions may be unsaleable by the time they are disposed of
Energy Recovery	Co-firing of slurries or use of waste heat boilers on incinerators		In use	

Technique	Description	Usage	Maturity	Notes
Scrap Metal Recovery	Resale of scrap metal from demilitarised munitions		Widespread use	Requires flashing or some method of removing contamination
Recycling as Fertiliser	Conversion of energetic materials to fertiliser		In use	
Chemical Conversion	Conversion of energetic materials to saleable chemical products		In use	Typical applications include production of phosphoric acid or picric acid
Energetics Recovery	Solvent based techniques to recover energetics from cross-linked binders	PBXs and rocket motors	In use	As a precursor to reuse as commercial or military explosives
Reuse as Commercial Explosive	Reuse of recovered energetics for commercial explosives	Recovered Energetics	In use	
Reuse Propellant as SAA	Reuse of high performance gun propellants in specialised small arms rounds	Gun propellant	Available	
Requalification for Military Use	Reuse of RDX or HMX in military applications	RDX and HMX	Research	

6.4 DISASSEMBLY AND REMOVAL

6.4.1 Mechanical Methods

Traditionally, disassembly involved a range of mechanical techniques. The goal of all of these techniques is to expose the energetic material for a removal technique to be used. Some types of disassembly techniques include:

- Reverse engineering by unscrewing of fuzes, fill plugs or baseplates,
- Use of a mechanical punch to pierce a munition,
- Crushing or pressing machines that break up a munition, and
- Cutting by use of a saw.

A variety of tools are required for this process. Sometimes these are generic industrial machinery such as the 'cracker mill' used for small arms ammunition deactivation.[57] Often, however, specific equipment will be required which is designed for the particular munitions nature. In Europe, this equipment is generally designed or modified for each demilitarisation activity. In the United States, commonly used equipment is codified and supported as Ammunition Peculiar Equipment (APE) by the Ammunition Equipment Division at Tooele Army Depot in Utah.

These techniques can be conducted manually however they require a skilled workforce and it may be difficult to meet safety requirements with manual methods. Increasingly therefore, robotics are being used to automate the process.

Mechanical methods can be used for energetics removal as well. The technique of contour drilling involves the use of a mechanical drill with a cam follower that allows the drill head to follow the inside of the projectile. The drill head cannot be allowed to pinch explosive against the shell wall so it is impossible to remove all of the filling. Typically 95% of the filling is removed by this method.

6.4.2 Fluid Jets

Fluid jet technologies utilise a pressurised fluid to cut or ablate materials. They have two main roles in demilitarisation:

- Disassembly in cutting or sectioning munitions. The most powerful can section the munition while in its casing. Less powerful jets might be used to reduce the size of uncased energetic materials for destruction.
- Removal by ablation or washout of energetic materials from a casing.

The fluid utilised can be water, in which case it is termed a water jet or another fluid such as liquid nitrogen or ammonia. One means of categorising fluid jets is as follows:[58]

Fluid Jet (FJ) – A process utilising high-pressure fluids, up to 410 MPa, forced through an orifice. The particle velocity of fluid jets is usually very high, up to a maximum of 1000 ms^{-1}, and is capable of directly cutting many low-yield-strength materials without the use of additional abrasives.

Abrasive Fluid Jet (AFJ) – A fluid jet that, after the fluid is accelerated through the orifice, entrains abrasive particles by aspiration and mixes them by mechanical action into the high-velocity stream of fluid inside a focusing tube. Depending on the abrasive and other parameters, abrasive fluid jets can cut through virtually any material. Most commonly the fluid used is water and this is termed an Abrasive Water Jet (AWJ).

Abrasive Slurry Jet (ASJ) – Also known as Direct Injection Abrasive Jets (DIAJET); a system that utilizes mixed fluid and abrasive slurry, which is then pressurized and the slurry mixture forced through a nozzle. Although abrasive slurry jets are potentially more efficient than abrasive fluid jets when operated at the same pressure, the current production equipment pressure levels are only about 20 percent that of abrasive fluid jets and have a proportionally lower efficiency. The distinction between AFJ where the abrasive is mixed at the nozzle and ASJ where the abrasive is mixed remote from the nozzle is illustrated in Figure 5.

Cavitating Fluid Jet (CFJ) – An intermediate-pressure, approximately 68 MPa, water stream process with a special nozzle that induces “natural cavitation” (vapour bubble formation) in the fluid flow. The cavitating fluid jet process involves the initiation, growth and impact of vapour bubbles against the target material. The collapse of these vapour bubbles causes intense, localized impacts in a highly variable manner to erode the target material.

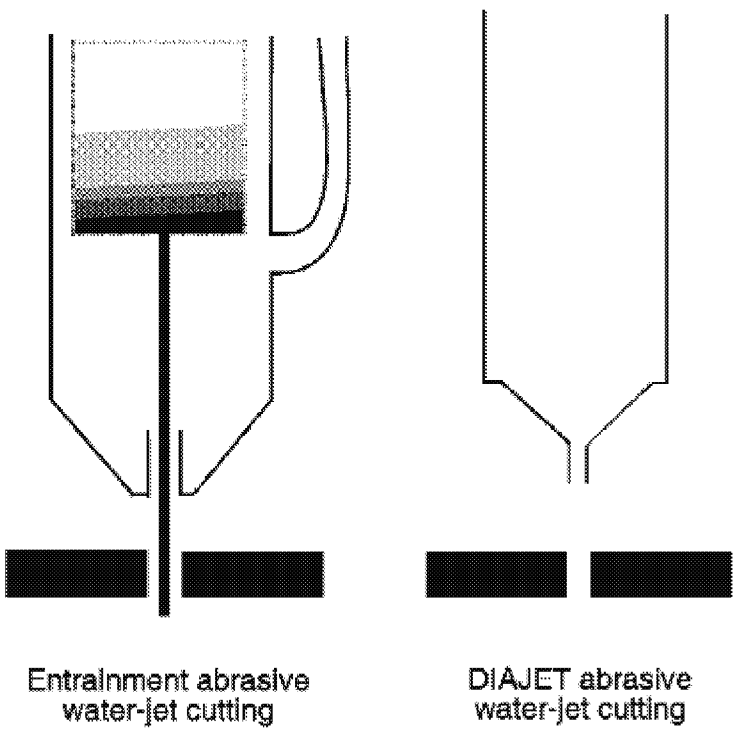

Figure 5 – Comparison of AWJ (left) and ASJ (right)[59]

Water and Slurry Jets

The use of water jets for demilitarisation dates at least as far back as 1924 when patents were issued to Knight in the US for a washout system for high explosive projectiles.[60] Increased pressure led to the use on tactical missiles in at the US Army Redstone Arsenal in 1954 and further increases in pressure were made by the US Navy in the 1970s. The use of water jets for cutting purposes originated with Franz in Canada in 1968 and the idea was commercialised by Ingersoll-Rand.[61] The use of abrasives to improve cutting performance was introduced in 1982 by Flow International however it was not until the 1990s that research was published on their use for disassembly of munitions.

Miller and Munoz[62] summarise the safety related information for water jets, both abrasive and non-abrasive. They argue that water jets at 350 MPa are acceptably safe with regard to impact sensitivity for use on high explosives and provide suggestions on dealing with other hazards associated with water jet demilitarisation. The key hazards are:

- Impact – from the jet, analogous to shaped charge jet impact;
- Electrostatic Discharge – from the rapid movement of water molecules;
- Mechanical Sparking – from abrasive materials (in particular garnet) on metal casings;
- Post Processing Reactions – this can be caused by reaction of the fluid with the explosive, with metal additives in the explosive, by abrasives sensitising the explosive or by contaminants such as paint or rust reacting with the explosive; and
- Industrial Hazards – associated with the operation of dangerous machinery in general and high pressure water jets in particular.

Evidence for a probability of initiation by impact of less than 1×10^{-6} for high explosives less sensitive than PETN is given by Miller and Miller.[63] This conclusion is backed by the evidence of large numbers of munitions (estimated at more than one million) cut by abrasive water jets without incident. Evidence also shows that mechanical sparking does not present a hazard. The remaining hazards can be dealt with by careful design and sensible engineering practices.

There is little literature on the use of cavitating water jets for demilitarisation purposes however Summers et al.[64] in 1987 suggest that the performance of non-cavitating jets is superior in washout applications.

The parameters affecting water jet performance are:

- Pressure
- Nozzle Design
- Abrasive Type, Size and Feed Rate (loading)
- Rate of Rotation of Munition

Burch et al.[65] and Summers et al.[66] have looked at the effect of AWJ parameters for sectioning a variety of projectiles ranging from 40 mm to 81 mm in calibre. They have identified economical abrasive loadings and pressure. Summers et al. also looked at nozzle type, abrasive type and recycling of abrasive with a view to reducing the cost of the technique.

Disadvantages of Water Jets

All forms of water or slurry jet demilitarisation suffer from a series of disadvantages:

- Generation of waste – although the flow rates are low due to the high pressures involved, water jet techniques still produce a large quantity of contaminated water. This waste water needs to be trapped and treated introducing considerable cost.
- Emulsions – water forms emulsions with many explosives. For example TNT forms ‘pink water’ which is toxic and difficult to dispose of.
- Explosive hazard – although water, in sufficient quantity, desensitises TNT, water wastes containing RDX and HMX can still detonate and propagate while in piping.
- Pyrophoric hazard – in particular with aluminised explosives in water.

With regard to the explosive hazard, research has shown that explosive slurries with 48% TNT and a stabilising agent can be classified as Hazard Class 4.1 in the UN system which is non-explosive and considerably easier to transport.[67] Other explosives still present an explosive hazard in slurry form.

As a result of these disadvantages, other fluids have been considered although none are as widely used and tested as water.

Alternative Fluid Jets

High pressure liquid nitrogen jets are considered an alternative to water jet technologies. Compared with water, the nitrogen is volatile and so does not add to the waste stream. It is also inert and non-toxic.

Muenchausen et al.[68] examined the cutting performance of liquid nitrogen. The jet can be used for abrading to remove explosive at below 100MPa. In the range 100-400MPa the jet can be used for cutting. Adequate cutting performance was achieved up to 1.5 inches in a HE surrogate. The technique is particular suited to recovery of energetics and has been used in rocket motor washout. The additional costs involved with managing cryogenic nitrogen at high pressures must be balanced against savings in waste treatment or energetics recovery. This technology is sometimes called ‘cryowashout’ and is utilised by General Atomics.

Anhydrous ammonia is considered as an alternative fluid for washout and cutting due to its ability to act as a solvent and desensitiser for a wide range of explosives. This eliminates two of the major problems with the waste stream of water jets – the formation of emulsions and that the waste retains explosive properties. Although ammonia is a toxic chemical, it is well understood and widely used in industrial applications. An additional benefit is that the liquification of ammonia can be achieved readily in ordinary stainless steel vessels compared with the stringent requirements for cryogenic liquid nitrogen.

Other fluids have been considered for specific purposes. Cannizzo and Miks[69] looked to a number of organic fluids with the aims of reducing ammonium perchlorate solubility and increasing cutting performance. They found promising results for propylene glycol and dipropylene glycol.

Carbon dioxide has also been investigated in a related but slightly different method referred to as blastout. Goldstein[70] reported on the use of pelletised carbon dioxide particles accelerated by a centrifuge to 1400 ft s^{-1} (427 ms^{-1}) to blast out the remaining explosive from shells demilitarised by contour drilling (see section 6.4.1). A prototype of this system is installed at Crane Army Ammunition Activity and has an anticipated throughput of six to ten projectiles per hour. A similar application has seen research into the use of blast out for decontamination of items without the damage caused by flashing.[71]

6.4.2.1 Fluid Jets in Use

Some recent examples of the use of fluid jets in demilitarisation include:

The use of high pressure water jets for washout applications is widespread. They have been used on items ranging from composite propellant rocket motors from strategic systems through to small high explosive filled projectiles. For strategic rocket motors, ATK Thiokol in the US is involved in demilitarisation by HP washout. The development of the tooling for this system was presented in 2002,[72] the small number of very large items allowing sophisticated, dedicated tooling to be developed. At the other end of the scale, Rheinmetall Waffe Munition (RWM) utilised a HP washout system to demilitarise a portion of the 220 000 tons of surplus munitions resulting from the reunification of Germany.[73] The RWM process involved a revolving nozzle at a pressure of approximately 20 MPa without added abrasive. The feed water did have additives to improve performance. Interestingly, RWM used this process successfully for a very wide range of natures and explosive contents although obviously the disassembly process was unique to each nature. The RWM equipment with the nozzle obscured is shown in Figure 6.

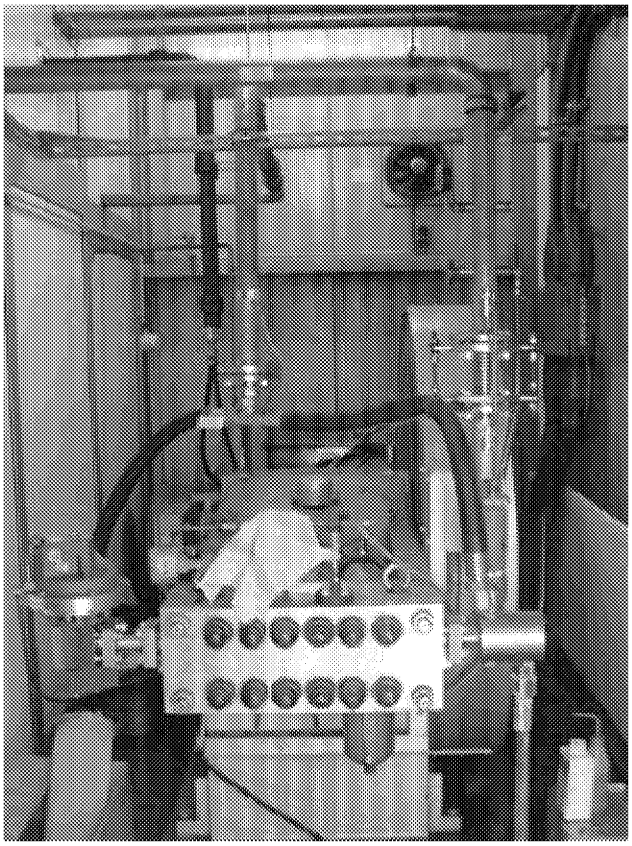

Figure 6 – Rheinmetall Waffe Munition High Pressure Washout Rig[74]

Miller[75] describes the use of AWJ for cutting at the former NSWC-White Oaks facility in 2003. In this case, during remediation over 1300 Munitions and Explosives of Concern (MEC) shapes were identified. These were largely inert shapes used for a variety of testing however 545 of the items could not be verified as inert. These shapes, which ranged up to Mk 84 2000 lb (907 kg) bombs in size, were demilitarised using a Gradient Technologies supplied AWJ system. The system was installed in a 20 ft ISO container, emplaced with HESCO barriers and operated remotely. The system operated at 380 MPa and cut up to a depth of 2.5 inches (63 mm) using 7.6 litres of water per minute. The potentially contaminated water effluent was trapped in the ISO container for treatment. The shapes, once sectioned, were inspected and the inert shapes and uncontaminated water were disposed of by usual means. Any suspect shapes or contaminated water were processed using a Donovan Blast Chamber on site. All of the shapes were processed in seven weeks.

Miller and Burcham[76] describe the installation of a demilitarisation system for fuzed naval shells loaded with Explosive D (ammonium picrate) at NSWC-Crane. The shells range from 3 inch to 8 inch in calibre (76 to 203 mm) and are base fuzed. The system runs a continuous process and is manually loaded in an area remote from the demilitarisation and fully automated throughout the remainder. An AWJ is used to cut up to 38 mm of steel to remove the base fuze. A water jet washout is then conducted to remove the explosive. Both the atmosphere and the water wastes are contained and treated due to the toxicity of the waste products. The water waste containing the explosive material can be recycled by chemical conversion. For 3 inch projectiles the system has achieved demilitarisation of 900 munitions in five hours.

6.4.3 Meltout

Meltout techniques use a variety of means to heat the energetic material in a munition to aid or cause its removal from the casing. As such the munition must go through some form of disassembly to allow the energetic material to be removed. Often, filling holes are insufficient for the purposes of removal and may not be useable by the time a munition is demilitarised so some form of reverse engineering or cutting will be required.

Meltout has a role in the removal of cast high explosives such as TNT, Comp B and Tritonal. Compositions that cannot be readily melted such as RDX, HMX and PBXs will not be suitable and liner materials can cause problems. Meltout techniques can be divided into two categories, those which use pressurised hot water or steam to melt the filling and those which use indirect methods. The most important indirect methods are microwave and induction meltout.

6.4.3.1 Autoclave and Steam Meltout

The US Ammunition Peculiar Equipment (APE) 1300 system utilises water jet nozzles at 180ºF (82ºC) and 100 psi (690 kPa) to recover cast explosives through the nose or base plugs. Due to the low temperature and pressure, this process generates very large amounts of waste water. Steam nozzles can also be used with the same disadvantage in waste generation. These systems are akin to very low pressure water jet systems but utilise hot water.

Development from the 1960s into autoclave systems led to its utilisation from the 1970s. More recently, an autoclave meltout system (APE 1401) was installed at the Crane Army Ammunition Activity (CAAA) in July 1994. Autoclaves involve the use of a pressurised vessel to heat water above the boiling point to melt a cast explosive which is then recovered for processing or destruction. The autoclave can apply the steam to the exterior of the munition only, thereby minimising waste water. For larger munitions, however, this process may be very slow and a steam lance akin to a water jet can be used inside the munition to improve speed at the expense of greater waste water production. A good overview of autoclave techniques is given by United Nations Development Programme's Bosnia and Herzegovina Demilitarization Feasibility Study.[77]

The system at CAAA involved an autoclave operating at 240ºF (115ºC) and a gas pressure of 15 psi (103 kPa). This was tested on munitions up to the size of 750lb (340kg) bombs and generated approximately one US gallon (3.8 litres) of pink water per hour. The estimated cost was only marginally greater than OB/OD costs however this does not include the cost of processing recovered explosive material and the waste pink water. The reported performance of the system is given in which Table 3 shows production rate per autoclave including a load/unload cycle.[78]

Table 3 – Performance of APE1401 Autoclave Meltout System

Item	Production Rate
90mm Projectiles	8 per 15 min
105mm Projectiles	12 per 20 min
120mm Projectiles	8 per 30 min
155mm Projectiles	6 per 50 min
175mm Projectiles	3 per 60 min
8 inch (203mm) Projectiles	3 per 75 min
750 lb (340kg) GP Bomb, Base Cut	1 per 155 min
750 lb (340kg) GP Bomb, Nose Fuze Well Cut and Removed	1 per 195 min

The layout of an Autoclave Meltout System when loaded with projectiles is shown in Figure 7. This type of system is in widespread use and Burnett[79] reported the installation of an APE 1401 in Egypt. The required processing of the molten explosives would depend on the composition of the energetic material, any liners or additives as contamination and the end use.

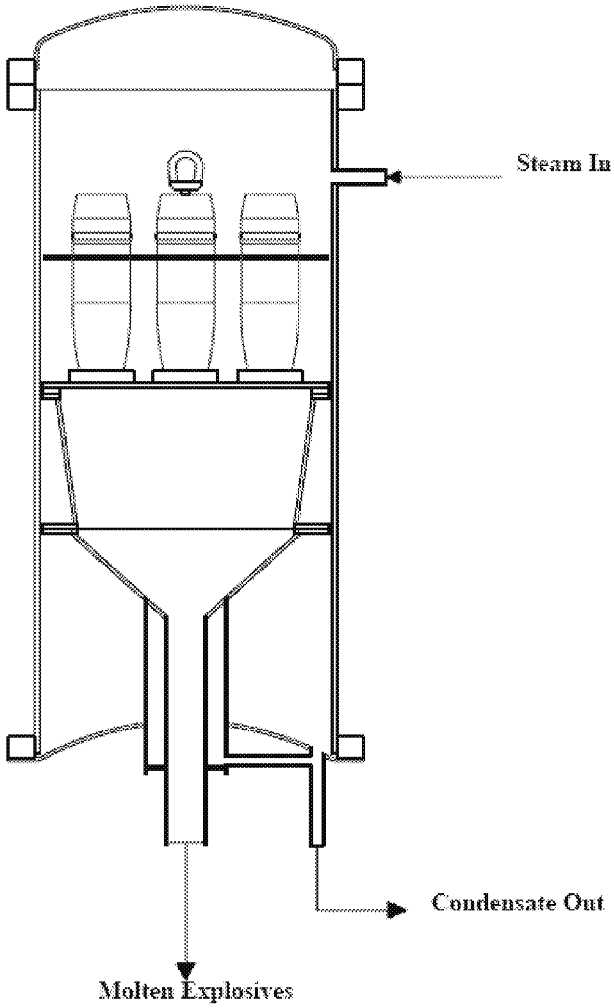

Figure 7 – Autoclave Meltout System Loaded with Projectiles[80]

6.4.3.2 Microwave Meltout

Microwave meltout has a number of advantages. It does not introduce water or steam to the energetic material. This yields high purity material that can be more readily reused. The absence of water also avoids the creation of contaminated wastes such as TNT contaminated pink water that are difficult to dispose of. Microwave meltout also has the potential to be more energy efficient than other meltout methods as the energy is transferred directly to the energetic material and relatively little is used to heat the munitions casing.

Initial research on microwave meltout was conducted in the 1970s and early 1980s however further development was shelved until the shift in focus to R^3 led to its resurrection. In 1998, Hayes and Frandsen[81] of El Dorado Engineering, Inc. published a paper on the use of microwave meltout. They looked at TNT, Tritonal, Comp B and H-6 and found that TNT and

Tritonal have the characteristic of absorbing less energy when they are heated above their melting point. This greatly reduces the risk of thermal runaway during the heating process. They found that the lower microwave frequencies trialled (915 and 2450 MHz) were superior as they have a longer attenuation distance which reduces the risk of overheating and give a more uniform heating pattern. This is offset by the difficulty of coupling low frequencies to munitions, particularly smaller munitions. The thermal properties also change with temperature with the microwaves penetrating further into cold explosives than into heated explosives.

Further research by El Dorado Engineering, Inc. using Tritonal filled M117 750lb (340kg) bombs[82] demonstrated approximately 99.6% recovery of the Tritonal. The trial required several safety measures, namely:

- Careful bonding of the bomb (with the base removed by cutting) and the equipment to prevent sparking,
- Remote operation,
- Monitoring of the bomb surface by IR camera with alarm levels linked to cutouts on the microwave to prevent hot spots and potential detonation,
- Preheating of the explosive surface with hot air to reduce depth of penetration of the microwave on startup, and
- Provision of a deluge system for the test bay and water jet nozzles for the bomb cavity;

There are no published reports of a pilot production plant for microwave meltout.

6.4.3.3 Induction Meltout

Induction meltout or heating involves the use of case as a conductor in an induced magnetic field. The magnetic field is created by a coil surrounding the case and an applied alternating current to that coil. The resulting changes in the magnetic field induce current in the case and therefore heat.

Since the heat is transferred by conduction from the case to the energetic material there will be a temperature gradient within the material with the hottest temperatures near the case. The need to allow time for the heat transfer limits how quickly the meltout can occur as applying excessive current will result in excessive surface temperatures. If the munition has been sectioned then it may be possible to melt the surface of the energetic material and have the remaining ‘plug’ fall out under gravity or be mechanically assisted with a push rod.

For induction meltout care needs to be taken to prevent sparking from the inductive coil to the casing. This could be achieved by a ceramic liner. An additional hazard can be vapour generated by heating the energetic material.

Burch et al.[83] reported some performance information on a prototype induction meltout system. Using 60 mm mortar rounds loaded with Composition B they found the average time to meltout was 11.9 seconds with a 4 kW source. They could improve this to 9.4 seconds when a push-rod was used to push out the partially melted slug. On average 99.1% of the filling was removed by this process.

6.4.3.4 Safety

The heating of an energetic material and the addition of impurities from the lining can affect the properties of the material. Mainiero et al.[84] looked at the effect of melt temperature and the presence of asphalt liner material on the sensitivity of TNT. The found that asphalt contamination does not significantly affect shock sensitivity but has an adverse effect on impact and thermal sensitivity.

6.4.4 Cryofracture

Cryofracture involves the use of a liquid nitrogen bath to embrittle munitions which are then fractured in a hydraulic press. Once fractured, the munitions are safe for further processing (such as incineration) as the risk of a high order event is eliminated.

The technique was developed by General Atomics in the US but is now widely utilised in both Europe and the US. The principal use is for the demilitarisation of small to medium size high explosive munitions such as hand grenades, mines and sub-munitions. These items are difficult to disassemble and still have a risk of detonation if incinerated following traditional mechanical means such as drilling or punching.

One alternative for disposal of small high explosive items is OB/OD; however, this is banned or at least heavily restricted in many countries (see Section 4.2.2). In addition, some of these munitions contain materials that would be unacceptable to dispose of in an uncontrolled manner. For example, the ADAM mine contains depleted uranium and the ability to incinerate these with the appropriate pollution control and to reduce exposure of operators to disassembled items is beneficial.[85]

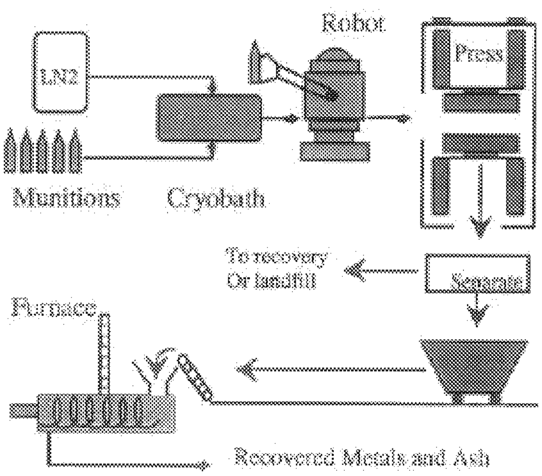

Figure 8 – Cryofracture Process Diagram[86]

6.4.5 Cryocycling

Cryocycling is the use of liquid nitrogen to rubblise propellant to uniform sizes for disposal or reuse. It has a particular role in the demilitarisation of rocket motors.

Between 1994 and 1996, Sandia National Laboratories undertook a study into cryocycling.[87] Their report describes the mechanism of cryocycling as follows. Contact with liquid nitrogen is used to induce thermal gradients within an energetic material. This in turn creates stress gradients and stress relieving cracks if the stresses exceed the local material strength. As the temperature is returned to ambient, further cracks are formed. When cracks intersect they cause rubblising, reducing the average size of the material. Multiple cycles causes further reduction in size although there are diminishing returns.

The advantages of cryocycling are that it does not add to the waste stream as the nitrogen is unreactive. This makes it easier to reuse and the material properties are largely unaffected by the process. In particular, as the temperature is maintained at or below ambient, the thermolytic processes of propellant degradation are not accelerated.

Sandia found that three to four cycles is sufficient to reduce bulk double base (NC/NG) propellants to fragments of 6-10 mm in size. They concluded that the technology is mature for non-case bonded double base rocket motors although proposing that the process could be applied to other solid propellants and high explosives.

General Atomics offer a cryocycling design for rocket propellants. This involves three cycles, each consisting of 15 minutes to fill the cryocycling bins with liquid nitrogen and cool followed by a two hour warm up. The final warm up goes for four hours and the resulting grains are classified to remove oversize grains (greater than ½ inch or 12.7 mm) for retreatment. The cryocycling and classification can be conducted remotely but the movement of cryocycling bins is manual. The entire process is designed to be completed in a 14 hour shift.

6.4.6 Ultrasonic

This technique involves the use of ultrasonic pulses to fragment cast-loaded energetic materials and is being investigated by ARDEC.[88] The ultrasonic pulses are used to cause cavitation in a liquid (calcium bromide solution) which causes fragmentation in an immersed solid. Experiments were conducted on TNT and Comp B simulants cast in 60 and 81mm mortar shells. Using a ½ inch (12.5mm) probe and a 375 watt, 20 kHz ultrasonic source removal times of under one hour were achieved and much improved times with a larger probe and boosted source. Testing on 10g samples of TNT and Comp B cast in beakers have shown that the explosives can be fragmented without detonation.

6.4.7 Laser Cutting and Machining

Some research has been undertaken in the use of lasers to cut explosives. This seemingly unlikely technique has been researched at Lawrence Livermore National Laboratories and involves the use of 'cold' femtosecond lasers to ablate material in pulses too short to cause significant heat transfer to materials.[89] Other research at Los Alamos National Laboratories has suggested that continuous wave laser could be used as the laser causes vaporisation that expels hot high explosive before bulk ignition occurs.[90] This could potentially offer a means of removing explosives with no generation of waste material however the technology is still immature for this application.

6.5 DESTRUCTION

6.5.1 Open Burning

The environmental impact of Open Burning (OB) is discussed in section 4.2.2. From a technology point of view, OB is a simple and unsophisticated technique. A typical protocol for open burning involves stacking the items on the burning ground and applying an accelerant to the furthest downwind item. This item is then ignited remotely and the burn propagates steadily upwind. More sophisticated approaches are possible and Garry and Smith[91] give a description of a system installed at Pantex in Texas. Some improvements are:

- Burning Pads – burning on open ground allows the direct contamination of the site with unburnt energetic material or other toxic products. Typically a burning pad consists of a steel tray lined with refractory bricks and lined with sand it may also be elevated off the ground. The collection of the sand after operation allows it to be dealt with as hazardous waste if required.
- Integrated Burners – gas burners allow a more controlled operation than accelerant and igniter which pose a hazard if ignition is not successful and human intervention is required. Installing burners at each corner of the burning pad allows ignition from the downwind direction regardless of prevailing conditions.
- Wet Explosives – these are dealt with by continual use of the burners (in essence open incineration) and wind screens to avoid spreading of the material.

The Canadian OB/OD studies[92] found that a key issue was ensuring complete combustion of the energetic material. The use of a burner based system would alleviate this as would careful choice of weather conditions to avoid excessive wind or rain that can prevent complete combustion. Although they found that although complete combustion of propellant

The US Army Corps of Engineers publishes guidance on temporary OB/OD sites.[93] Roughly equivalent guidance exists for a number of other militaries. The US Army pamphlet is chiefly concerned with safety and security. A selection of relevant guidance includes measures to:

- Prevent spread of fire from the open burning site. This includes limits on prevailing wind speed, instructions for clearance of combustible material from the site and inter-site spacing.
- Prevent detonation. This is achieved by limiting the depth of material such that the critical diameter (or height) of a normally non-detonating material cannot be reached.
- Protect personnel. This includes Personal Protective Equipment (PPE), safety distances for flame or projectile hazards and also the use of pit or trench burning for items with a danger of propulsive burning.
- Prevent contamination through the use of burning pads.
- General requirements on training, communication, security and planning.

6.5.2 Open Detonation

The environmental impact of Open Detonation (OD) is discussed in section 4.2.2. As a technique, OD is relatively simple however due to the hazards involved in detonation of items it requires some degree of sophistication and careful control.

Typically OD involves the stacking of the items for destruction and then the use of a donor charge to initiate the items. The key requirement during OD is to ensure detonation of all items and to reduce projection hazards. In particular, projection of unreacted ordnance can cause difficulties. Ensuring complete detonation will be achieved by careful planning by the personnel involved. Typically the donor charges will be demolition charges however it may be possible to use explosives recovered from other demilitiarisation processes or even improvised means such as initiating a particular class of munition (eg. anti-tank mines) as a donor for another type of munition. Shaped charges may be the only way of ensuring detonation, particularly with insensitive munitions.

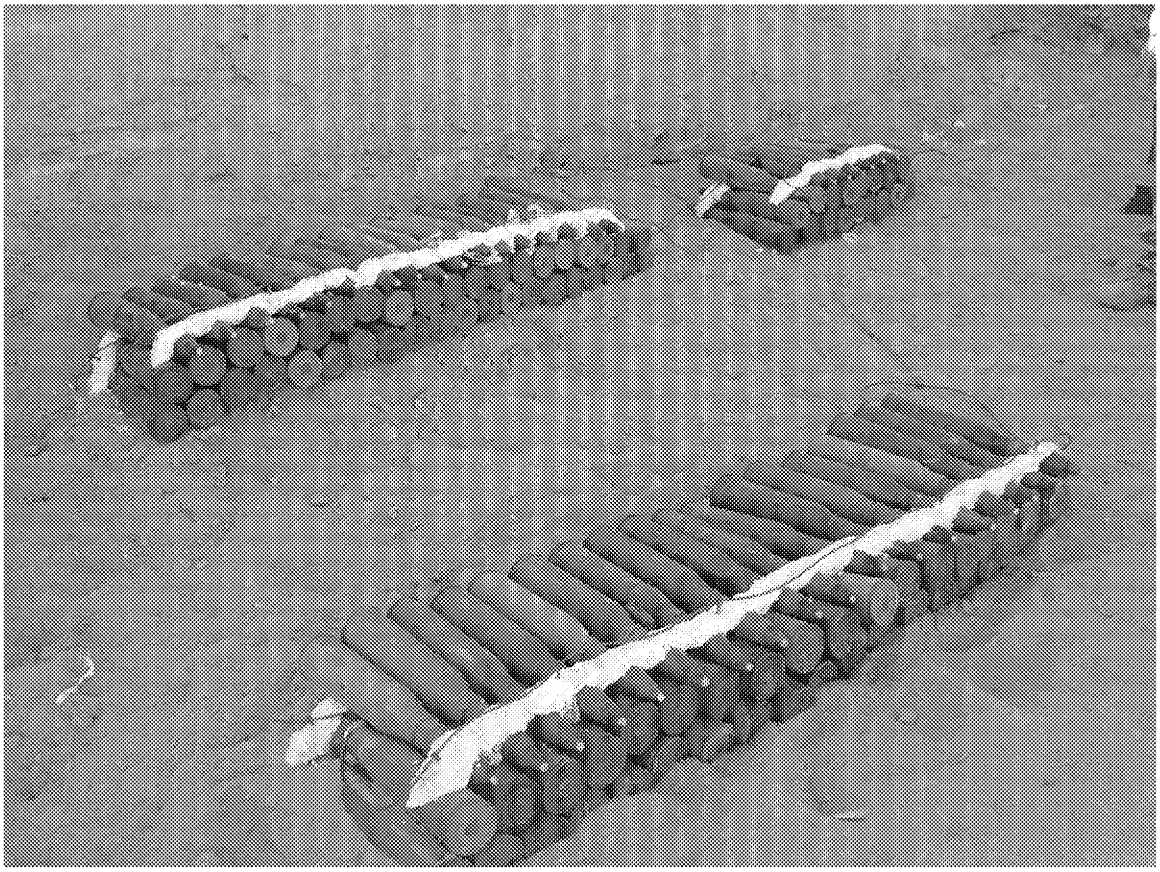

Figure 9 – Iraqi Munitions Prepared for OD by British Royal Engineers[94]

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Projection hazards can be minimised by safety distances and also engineering controls such as sandbagging, earth berms, earth covered detonation (earthen overburden) and protective enclosures for personnel. As discussed in section 6.5.1, the US Army Corps of Engineers issues guidance on temporary OB/OD sites[95] many of the issues for OB are also applicable to OD. The largest difference being the required safety distances to personnel shelters, inhabited buildings etc.

As discussed under environmental impacts, the noise generated by OD is a concern and also a limit on the use of OD sites. A number of measures have been considered for mitigation of noise for OD. Calderone and Garbin[96] examined three techniques:

- Application of an earthen overburden;
- Aqueous Foam; and
- Rubber and Steel blast mates.

They found that the earthen overburden technique provided significant noise reduction and that other techniques reduce blast overpressure, they did not significantly reduce overall noise levels transmitted off range. Meteorological conditions have a significant effect on the transmission of noise off range. As a result, many nations place restrictions on OD under particular weather conditions such as low cloud cover.

The cost effectiveness of OD compared with other techniques such as incineration is difficult to gauge. In countries such as Australia, Canada, the US and Finland the availability of large, remote OD sites allows very large OD activities to be conducted with resulting savings. In most of Europe on the other hand, where OD is permitted for demilitarisation (as opposed to essential blow-in-place on UXO), the sites are likely to have much smaller limits due to the proximity of inhabited areas.[97] This results in higher costs, both due to increased labour and also materials as generally more donor charges will be required for a larger number of smaller events.

One particular and currently unique application of OD for demilitarisation is undertaken by Nammo in Norway. At a site in Løkken Verk, southwest of Trondheim, Nammo NAD utilise a copper mine shaft to detonate munitions more than 800m below ground. Emissions are monitored at the surface but the water filled mine shafts act as a natural scrubbing system. The mine has a natural inflow of 30 000 m^3 of water per year which is pumped out to another disused mine and analysed by the Norwegian Institute for Water Research (NIVA).[98]

Figure 10 – Ammunition Disposal by Underground Detonation at Nammo NAD[99]

6.5.3 Contained Detonation

An alternative to open detonation is contained or controlled detonation. This involves the detonation of material by a donor charge within a chamber that allows the pressure, fragmentation and noise effects of the detonation to be controlled and the emissions to be treated. The most common contained detonation chamber is the so-called Donovan Chamber developed by John Donovan of DeMil International although other products such as Teledyne-Brown Engineering's Mobile Detonation Chamber System are available. The Dynasafe AB Static Kiln is more properly an incineration method as it does not use a donor charge and this is covered in that section.

The Donovan chamber is essentially a large steel pressure vessel. It consists of an inner and an outer layer of steel plate welded to an I-beam frame. The void between the steel plates is filled with dry silica sand to reduce noise and shock. Replaceable armour plates cover the inside walls to prevent fragmentation damage and a layer of gravel likewise protects the floor. Fragmenting ammunition is encased by the donor charge to further reduce shrapnel. Water bags are suspended from the ceiling which reduces heat effects in the chamber.

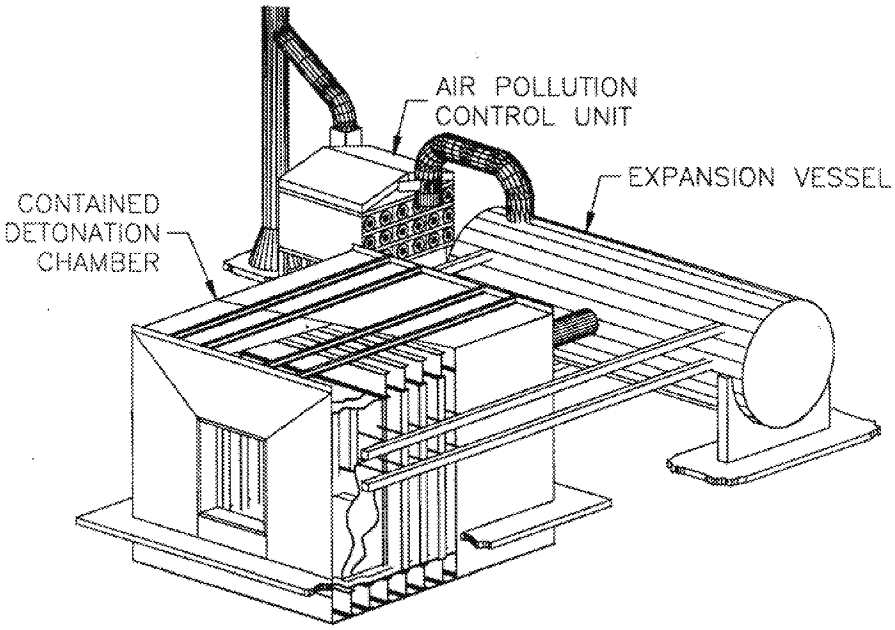

Figure 11 – Donovan Contained Detonation Chamber[100]

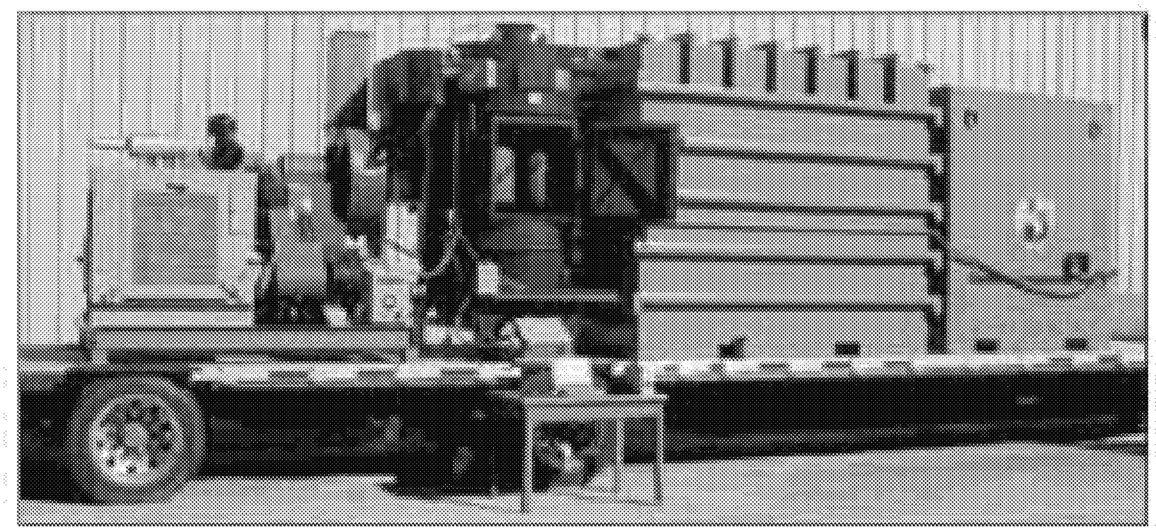

Figure 12 – Donovan Contained Detonation Chamber[101]

As a batch process, the contained detonation chamber is not readily suitable for industrial scale demilitarisation. It does fulfil a number of roles however:

- It is suitable for destruction of UXO on site during site remediation activities. Although in some situations it is unsafe to move the UXO and it must be blown in place, where movement is possible a contained detonation chamber could be used.

- For experimental or prototype munitions where the quantity and variety make industrial scale demilitarisation unfeasible.
- For munitions with particular hazards that make disassembly or OB/OD unsafe options such as non-stockpile chemical munitions.

6.5.4 Contained Burn

Contained burn systems involve the use of a containment building to ignite rocket motors. The technique is akin to static firings used in rocket motor development as the motors are ignited by their firing systems so an external burner or donor charge is not required.

The US developed the Tactical Demilitarization Development (TaDD) system[102] in the late 1990s, functionally testing a prototype in 1999 and 2000. The system consists of a containment vessel with a capacity of 73.6 m^3 which contains a holder for the rocket motor. After firing the contents of the vessel are passed through a pollution control system to ensure emission requirements are met. The rocket motor would then be subject to further demilitarisation activities to disassemble and dispose of or recover the non-energetic components.

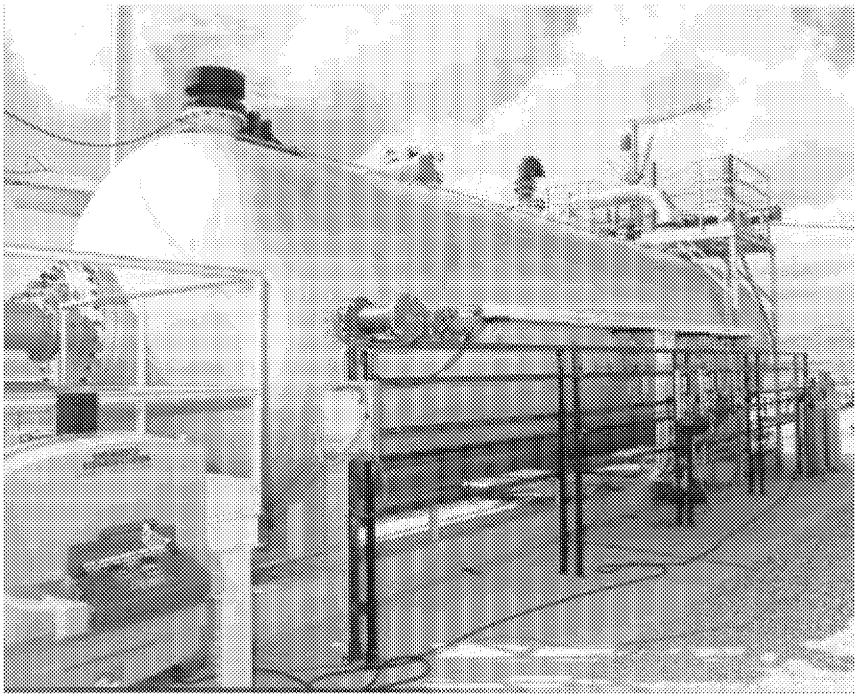

Figure 13 – Containment Vessel for TaDD[103]

The system fills a niche role and has a number of advantages:

- Not an incinerator – the system does not employ a burner it is not classed as an incinerator and therefore may be easier to obtain permits for.
- Road transportable – the system can be moved to storage locations to reduce transportation of munitions.
- Low energy consumption

The system is limited by being a batch process and thus is unsuited to very large demilitarisation projects. It can only be used on rocket motors and some analysis of the safety of the motor under increased pressure in the containment vessel would be required.

6.5.5 Incineration

Incineration involves the heating of waste, in this case explosive waste, to cause decomposition. Unlike detonation chambers, they are not primarily intended to withstand detonations of material although static and rotary kilns may be armoured to deal with moderate amounts of detonable material. Although the term incineration can cover many forms of thermal treatment including open and contained burning, it is normally used for controlled and contained treatment using an external heat source.

Incineration is variously referred to as thermal treatment, thermal destruction and thermal disposal. The incinerators are known as Explosive Waste Incinerators (EWI), Hazardous Waste Incinerators (HWI), deactivation furnaces or simply by their type such as rotary kilns. If used as a fuel in co-firing then the device may be termed a combustor, reactor or boiler.

6.5.5.1 Static Kiln

Static kilns are sealed chambers which are capable of heating the contents to induce deflagration or detonation. Dynasafe AB (Sweden) produce a range of static kilns which utilise indirect heating to avoid adding additional gas to the emissions. The kilns come in capacities ranging from 800g to 10kg NEQ and Dynasafe AB claim that destruction rates up to 40kg per hour are capable. They operate on consecutive firings as opposed to a continuous feed mechanism. Unlike a controlled detonation chamber, the static kiln does not utilise a donor charge to cause detonation and in fact burning or deflagration may be the only effect.

Figure 14 – Static Kiln from Dynasafe AB[104]

The static kiln is an alternative to the rotary kiln for demilitarisation of small arms and other small items although it may also be used for small quantities of high explosives or propellants.

6.5.5.2 Rotary Kiln

The most common type of incinerator for explosives is the rotary kiln. They are normally made of a number of retort sections (or chambers) bolted together. The sections may be lined like a traditional furnace or alternatively they may be 'armoured', made of steel up to 80mm thick, to resist detonations and suppress fragment throw from small items. Internally the kiln contains spiral flights that move the waste in the manner of an Archimedes screw through the retorts as the kiln rotates. The flights allow the kiln to be operated continuously and discourage sympathetic interactions between materials. Varying the rate of rotation allows the residence time for the waste to be altered so that different types of munitions can be easily dealt with. A typical residence time is around 30 minutes. The burner for the kiln will run on fuel oil, natural gas or propane and provides a gas temperature inside the kiln in the range 600 – 1500ºF (316 – 820ºC).

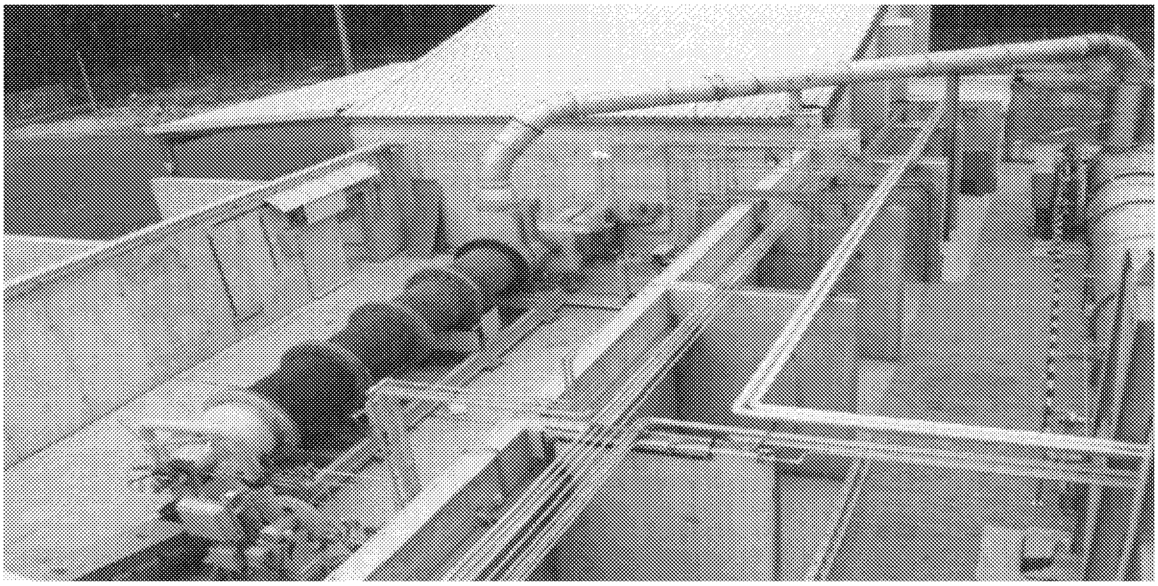

Figure 15 – Rotary Kiln at ISL, Germany[105]

The kiln may have a standard conveyer belt feed system. This will utilise a feed chute and gravity to ensure that there is no direct line-of-sight from the first section of the kiln. Alternatively, a positive feed system can be used where containers of material are injected into the kiln using a ram. This is normally used for bulk granular or powdered explosives where spilling is a concern. The gas emissions will be collected for treatment by a pollution control system. The solid components, consisting of scrap metal and ash, will be discharged by a conveyer for recycling or disposal by landfill.

Rotary kilns can handle bulk propellants, high explosives, small arms and small detonable items such as fuzes, detonators and squibs. The ability to handle high explosive and the size of small arms and detonable items that can be treated will depend on the wall thickness of the kiln. Other forms of treatment can be utilised to ensure that items are not capable of a high order event and this may allow then to be disposed of in a rotary kiln.

The most common rotary kiln design, both in the US and worldwide, is the US Ammunition Peculiar Equipment (APE) 1236. Referred to as a deactivation furnace, the APE 1236 can be used for small explosive items (small arms, fuzes and squibs etc), bulk propellants and for flashing (ie. removing residual explosive contamination) of larger projectiles (76 mm – 120 mm). Typical explosive limits for this device are 39 g per item for 2 ¼ inch (57 mm) walls and 52 g per item for 3 ¼ inch (83 mm) walls with a feed rate of one item per second.[106] The M1 model is modified to meet RCRA requirement for hazardous waste incinerators. It has an afterburner at 1700°C for gas emissions, high and low temperature gas coolers, cyclone and baghouse for pollution control. The most recent M2 model has an improved ceramic baghouse, removes the high and low temperature coolers and updates the control panels.

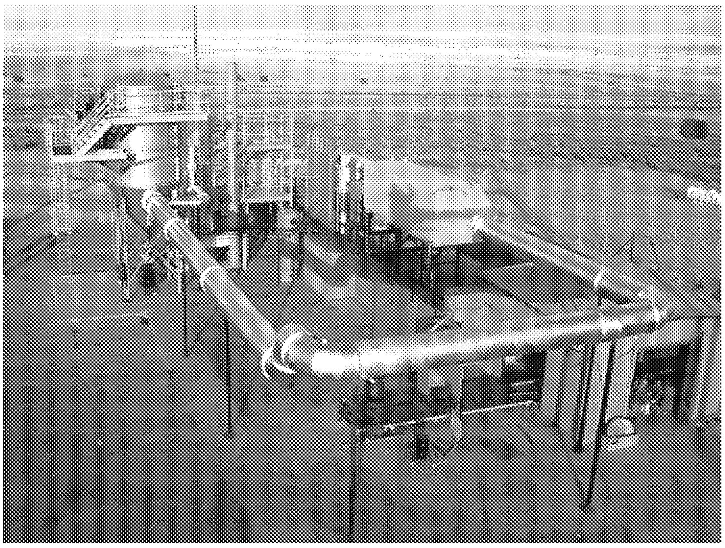

Figure 16 – APE 1236 M2 Deactivation Furnace[107]

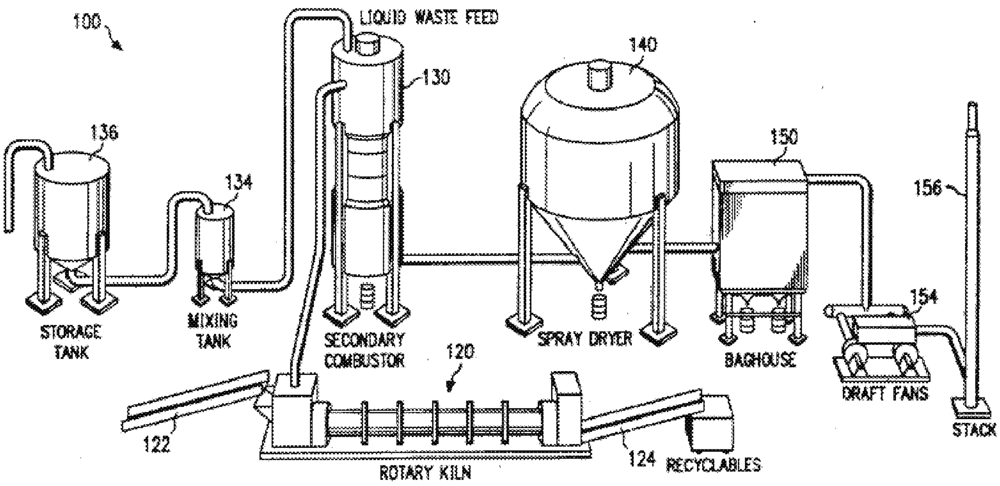

Figure 17 – Explosive Waste Incinerator[108]

6.5.5.3 Car Bottom Furnace

These are used for incineration of explosive contaminated waste and flashing. The furnace consists of a fixed refractory lined furnace and a 'car' which is normally rail mounted for loading external to the furnace. This is then moved into the furnace and facilitates batch processing of large loads that would be awkward or dangerous to load directly into the furnace.

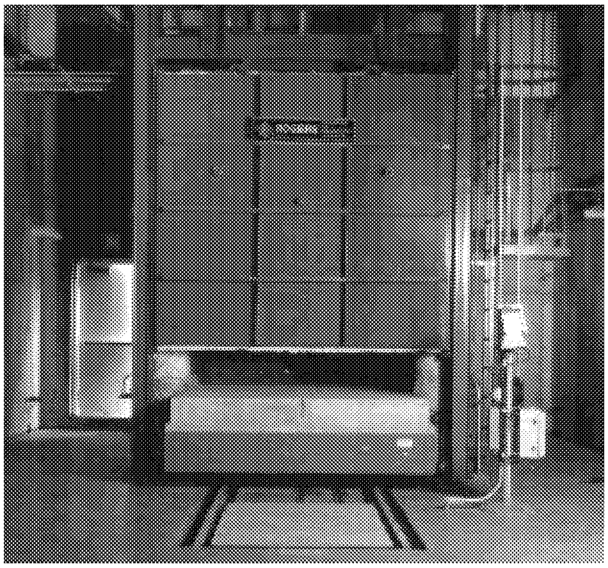

Figure 18 – Car Bottom Furnace at EBV EEC in Joplin, Missouri[109]

Car bottom furnaces are often found as adjuncts to rotary kilns sharing a common pollution control system. Numerous other specific furnace designs can be utilised for flashing and contaminated waste destruction. These applications are characterised by limited hazard posed by the material and alternative furnace designs may meet local operational requirements.

6.5.5.4 Plasma Arc

Plasma Arc thermal treatment involves the generation of a plasma arc at temperatures of up to 11000ºC between two electrodes or an electrode and ground to destroy munitions. Plasma Arc techniques have a niche role for demilitarisation of obsolete or unserviceable small, assembled pyrotechnic munitions. These are difficult to destroy with OB/OD or conventional incineration due to the generation of a large amount of particulate matter and local temperature hot spots. The effluent streams from plasma arc techniques are relatively benign compared to furnaces however their ability to handle detonable materials is limited.

The US Army has developed a Plasma Ordnance Demilitarization System (PODS). PODS involves a chamber which is pre-filled with an amount of iron and soil which are melted to form a molten slag. Munitions are fed into the chamber and drop into the slag where they combust. The gas above the slag is kept oxygen rich which ensures that all organic and inorganic substances are destroyed or oxidised in the hot gas or the slag. The chamber gas temperature is kept at 2000-2500ºF (1093-1371ºC) and the molten slag pool at 2500-3000ºF (1371-1649ºC). The slag encapsulates all hazardous material and passes EPA tests for leachability and hence can be treated as non-hazardous waste. The amount of HD1.1 or 1.2 material per load is very limited at approximately 90g.[110]

There is a pollution control system to deal with hot gas waste, similar to those found on rotary kiln furnaces, although the volume of emission is greatly reduced compared to fossil fuel fired kilns. The system is installed at Hawthorne Army Depot, Nevada and was expected to be operational in FY 04.

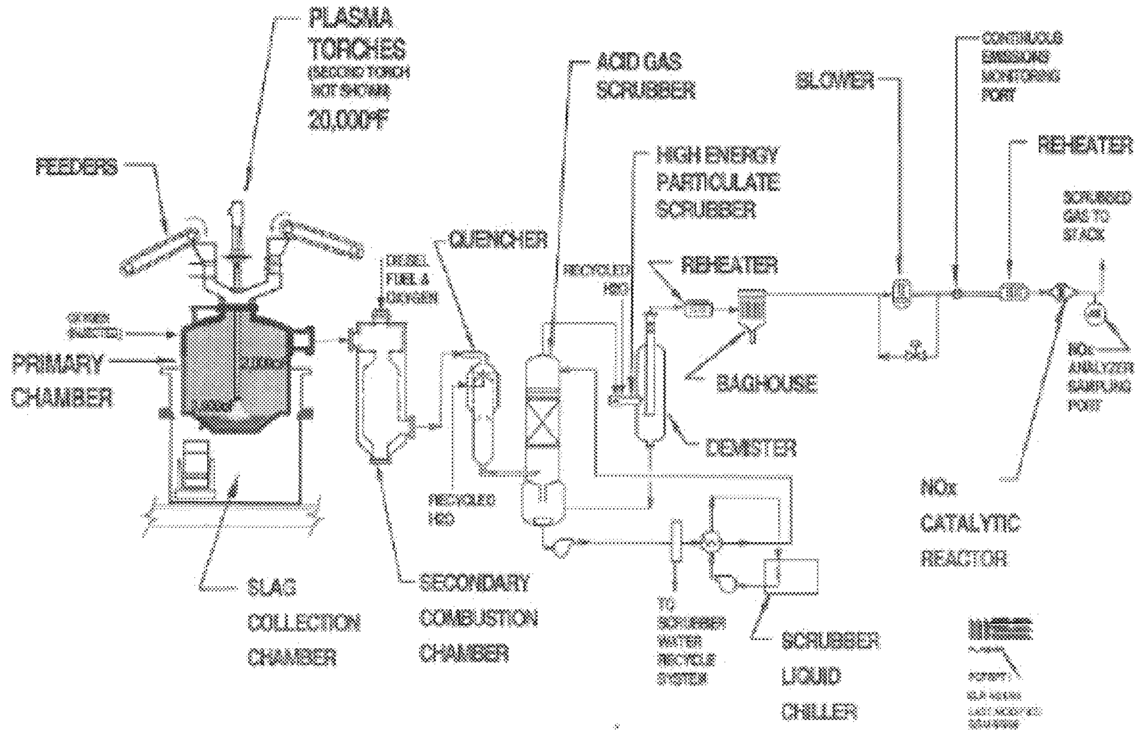

Figure 19 – Plasma Ordnance Demilitarisation System[111]

The US Army has also developed a smaller Mobile Plasma Treatment System (MPTS). This systems has around one third of the capacity of PODS but is transportable on eight to nine standard flatbed trailers and occupies a site footprint of around 100 ft x 100 ft (30.5m x 30.5m). Although the capacity is reduced, the furnace is not lined with refractory bricks and the walls are thicker so that it can actually handle an increase amount of HD1.1 or 1.2 per load (150g).

An additional feature of the MPTS is that it can be used in an oxidising mode (where additional oxygen is fed into the system) or in a reducing mode (with a nitrogen co-feed). The former mode is ideal for ensuring complete oxidation of pyrotechnic by-products but the later can be more efficient for recovery of metals for recycling when used with relatively benign munitions such as fuzes.

6.5.5.5 Fluidised Bed

Fluidised bed combustors work on the principle of suspending solids on upward-blowing jets of air to create a turbulent fluid mix to aid combustion. The system can be used in a number of ways:

- Solid fuel can be fluidised and an explosive waste slurry injected at up to 25% of the fuel intake. This technique is commonly used to create cleaner coal burning power plants and the addition of a waste slurry would be a form of co-firing.
- A bed of granular particles (for example sand or sintered alumina) can be fluidised and heated by an oil or gas burner and a solid or slurry waste stream injected. The fluidised sand will act to break up the waste stream and then combust it as heat is transferred. This technique is commonly used in municipal waste incinerators.
- The concept can be used for non-thermal treatments such as an anaerobic fluidised bed reactor used for biological treatment of pink water. This application will be covered elsewhere.

By virtue of the turbulent mixing, combustion is improved. As a result, near complete combustion can be achieved at lower temperatures than would otherwise be required. This can improve efficiency and the lower temperature will also suppress the formation of acidic gases such as NO_x. This is particularly an issue with explosive waste due to the generally high nitrogen content of the material. Ammonia can be injected as an additive to further suppress the formation of NO_x and the effect of this on nitro-methane slurries has been studied.[112] The same study also found that with precautions, the slurry could safely be incinerated without an explosive hazard.

Temperatures for fluidised bed combustors can be as low as 500ºC[113] although typical temperatures are around 800ºC. Stable combustion at low temperatures is very efficient and this is a major advantage for these systems however there is a potential conflict with legislation related to minimum temperatures for hazardous waste incineration.

Fluidised bed combustors are in use as a cleaner way to burn fossil fuels and to incinerate municipal waste. Research into their use for explosive waste incineration has been undertaken for a number of years and indeed a prototype plant was run at the Picatinny Arsenal, New Jersey during the 1970s and favourably reported on. [114] However, the technology was abandoned and despite some recent research there are believed to be no production plants handling high explosive or propellant wastes. Related plants for the incineration of material such as riot control agents and pyrotechnics are in use, for example at the Pine Bluff Arsenal, Arkansas. The use of fluidised bed incinerators for pyrotechnics is limited, however, by the tendency of light metal salts formed during incineration to clog up the fluidised bed.

6.5.5.6 Molten Metal Pyrolysis

The pyrolysis reaction involves the decomposition of organic materials by heat in the absence of oxygen. Molten metal pyrolysis utilises metals (typically copper, iron or cobalt) at around 1650ºC and produces gaseous emission and a slag.[115] Although very efficient at destroying organic matter, the emission gases still require treatment and the operating conditions are difficult and expensive to achieve. Some research was conducted in the context of destruction of chemical munitions however little work appears to have been conducted recently for conventional munitions demilitarisation.

6.5.5.7 Pollution Control Systems

Incineration plants will have a Pollution Control System (PCS) to enable them to meet the emission levels set down by national legislation (or international regulations embodied in national legislation). The details of significant regulations can be found in section 4.2.3.1, this section will focus on the technology used to meet these requirements. An overview of pollution control systems can be found in the International Mine Action Standards[116] and also in the United Nations Development Programme Feasibility Study.[117]

The PCS needs to meet regulatory temperature requirements and to handle a range of pollutants including:

- Volatile Organic Compounds (VOC);
- particulate matter;
- acidic gases (ie. NO_x and SO_2);
- heavy metals; and
- dioxins.

Most plants meet the temperature requirements in EU legislation by use of an afterburner or secondary combustor immediately after the kiln. These generally operate in the 1200-1700ºC range which is sufficient to destroy VOC and reduce the formation of dioxins. The VOC are converted to carbon dioxide, water and acidic gases. To meet the EU requirements a gas residence time of at least two seconds is required. Ammonia can be injected during afterburning to reduce the formation of nitrogen oxides (NO_x).

Following the afterburner there must be a mechanism to cool the hot gases to prevent damage the remainder of the system. Damage could occur by inducing unwanted heat treatment of steel components or potentially inducing fires. Fire is particularly a risk with baghouse filter systems. Cooling is normally done by water spray and reduces the gas temperature to around 500ºC. A waste heat boiler could be introduced at this stage to recover some energy from the process.

To absorb the acidic gases, a scrubber system is required. The scrubber uses water with an alkaline salt added to remove and neutralise the NO_x and sulphur dioxide (SO_2). Three main types of scrubber are used which vary in how they impact the liquid with the gas stream:

- Venturi system use a venturi nozzle to accelerate the gas stream and the liquid is then injected and is atomised leading to efficient scrubbing of the gas stream.
- Packed systems use specially shaped objects in a tower to generate turbulence and mixing of the liquid and gas.
- Spray systems rely on the spray of liquid droplets to mix with the gas stream and scrub acidic gases.

Systems of this nature to deal with NO_x would be unlikely to be found on US incinerators as they add considerably to the expense and there is no NO_x limit in US regulation. El Dorado Engineering have estimated the cost of providing NO_x control to EU limits at US$1 million.[118]

The removal of particulates can be achieved by a dry ceramic filtration system or the cheaper baghouse system which uses Gore-Tex/Teflon filter bags. The dry ceramic system has been used in Europe (in particular at the Shewburyness facility) and is claimed to be more efficient and reduce fire risk. The baghouse system is still predominant in the US.

To absorb heavy metals, in particular mercury from the gas, an activated charcoal bed can be used. The activated charcoal will also pick up remaining VOC.

Finally the PCS will feature some form of monitoring system to ensure that emissions levels are being met. In some cases this may be linked to an automatic plant shut-down if emissions are exceeded.

A typical rotary kiln with PCS is illustrated overleaf. This is EST's system at Steinbach in Germany which features two rotary kilns feeding a common PCS. After the afterburner (at 1200ºC) it has a waste heat boiler to allow recovery of some of the energy from the process (750kW). The spray cooler reduces the temperature further for the bag filters which is followed by three gas washes (acidic, basic and then neutral). There is also a catalytic NO_x remover which uses urea to further reduce NO_x emissions. The entire system has an automatic monitoring system linked to plant shut-down.

By comparison, fluid bed systems have a simpler PCS using absorption trays to remove VOC. The absorber is itself fluidised and can be regenerated in a desorber. This generates a concentrated waste stream that is more easily disposed of by afterburning.

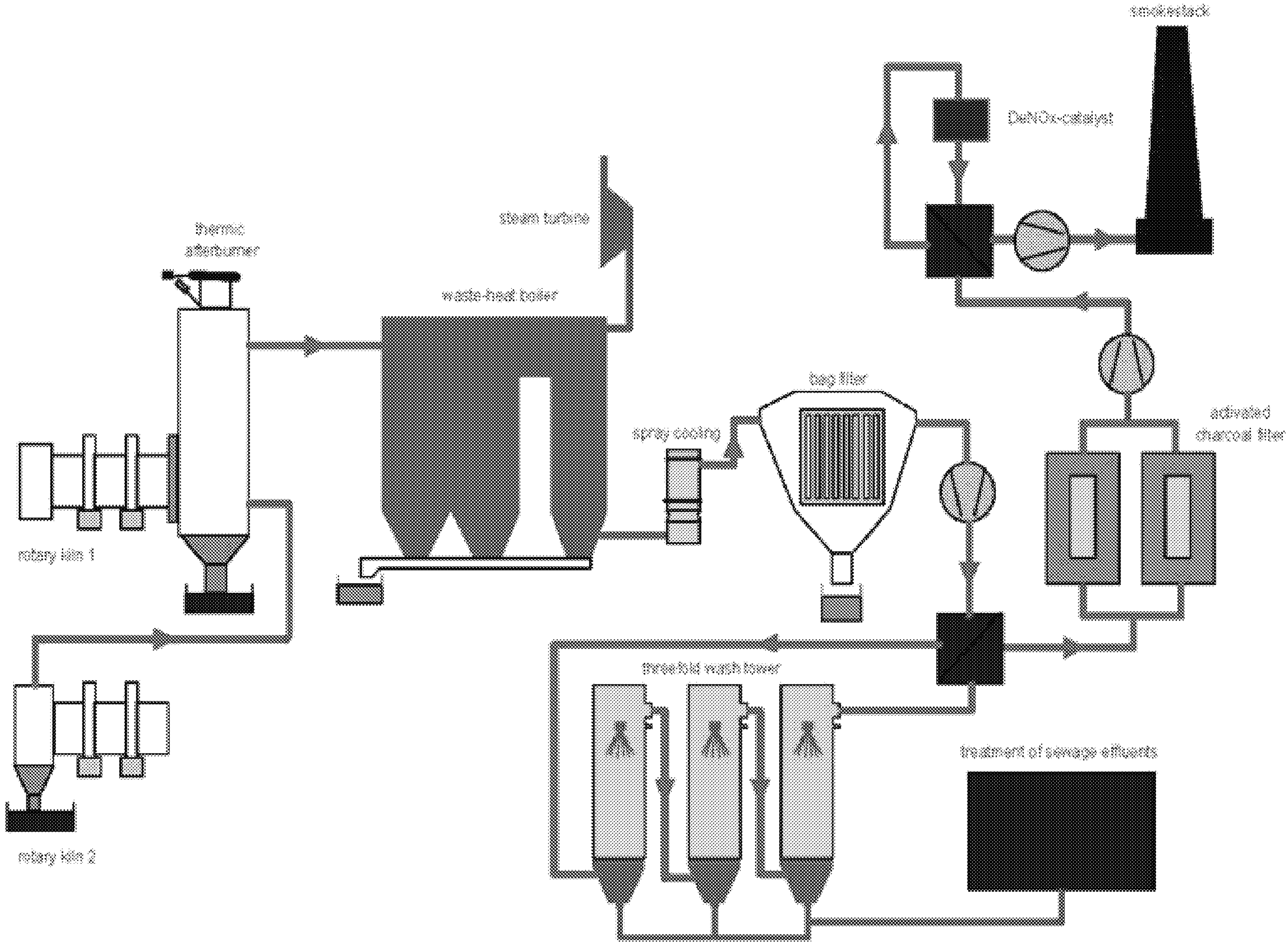
smokestack
DeNOx-catalyst
steam turbine
thermic afterburner
waste-heat boiler
bag filter
spray cooling
activated charcoal filter
rotary kiln 1
rotary kiln 2
threefold wash tower
treatment of sewage effluents

Figure 20 – Schematic of Rotary Kilns at EST, Germany[119]

6.5.6 Oxidation

Oxidation is used as a method of hazardous waste treatment and involves a Reduction-Oxidation (REDOX) reaction where electrons are provided from one compound to another. This generally yields less reactive and less hazardous materials and indeed combustion is a form of rapid oxidation where organic compounds are transformed to their oxides. This section is concerned with industrial scale chemical oxidation and each of the potential processes will be considered in turn. Many of these processes were developed with more toxic wastes in mind and in fact the development of several has been promoted by the need to dispose of chemical weapon stockpiles. Many other oxidation processes could be used and have been considered for destruction of energetic materials, see for example Blanch et al. on the oxidation of NTO.[120]

Oxidation techniques involve reaction of the energetic material to form less toxic products which can be more easily treated. These products will almost always require further treatment although ideally they would be treated by conventional waste treatment systems. The ultimate goal of oxidation would be complete mineralisation. That is that all of the organic compounds are converted to inorganic compounds such as carbon dioxide, nitrogen, water.

6.5.6.1 Alkaline Hydrolysis

Alkaline Hydrolysis (also known as caustic or base hydrolysis) utilises the hydrolysis reaction to convert explosive or toxic chemicals to less explosive and toxic chemicals. The hydrolysis reaction consists of the cleaving of a molecule into two parts and the addition of a water molecule in the form of a H^+ and OH^- ions. An excellent review of the chemistry of hydrolysis for the destruction of energetic materials is found in a review for the Assembled Chemical Weapon Assessment (ACWA) Programme.[121] This review will not attempt to revisit this area but instead concentrate on the application of the technique to conventional weapons demilitarisation.

Current approaches to alkaline hydrolysis utilise a reactor vessel at elevated temperatures (60 – 155 ºC), possibly at elevated pressure and in the presences of a strong alkaline solution. The energetic materials react with the alkaline solution to form various products. The type of products is dependant on the material being treated, the ratio of solution to energetic material and the conditions. It is seen as having a role replacing thermal treatments for high explosives and propellants due to potentially very low emissions. As well as removing the energetic nature of the materials, the hydrolysis will also render the products soluble for other treatments.

The key issues with successful use of alkaline hydrolysis are:

- Characterisation of the intermediate and final products to ensure safety in the process and that the final product can be treated.
- Difficult to mix different compositions in the same reactor due to the variation in the reaction speed for different energetic materials.
- Hydrolysis is a decomposition reaction and will be exothermic with energetic materials. Measures need to be taken to prevent thermal runaway and the reactor must be capable of containing the maximum credible event.

- Speed of reaction is related to the reacting surface area, therefore, preprocessing will be required to reduce the size of particles for many munitions.

Examples of current or planned hydrolysis treatment plants include:

United Technologies Corporation (Pratt and Whitney Space Propulsion) has a plant in San Jose, California which includes a hydrolysis plant for treatment of waste propellant and propellant contaminated materials. The process involves a 148 gallon (560 litre) reaction vessel using sodium hydroxide. The plant has a capacity of 200 lbs (90.7 kg) per day[122] and uses mechanical shredding to reduce wastes for processing. The waste water is treated as hazardous waste and incinerated in an appropriate facility off-site.[123]

UXB International developed a pilot plant for treatment of contaminated soil.[124] In this application, due to the location of the former propellant production site in New Jersey it was not possible to treat by thermal means on-site, nor to transport the contaminated soil off-site. A pilot hydrolysis plant was set up running at up to 1000 lbs (454 kg) per day. The hydrolysate resulting from the process could be transported off-site for further treatment but was still hazardous waste due to the residual level of 2,4-dinitrotoluene (DNT).

The UK "Demil 2000" programme looked at alternative methods of demilitarisation and proposed a system based on Abrasive Waterjet Cutting (section 0), alkaline hydrolysis and a combination of photocatalysis and bioremediation. On completion of this the effluents are intended to be dischargeable to a normal sewage treatment works. The programme successfully conducted 30 litre scale testing of the hydrolysis component.[125]

Cartridge Actuated Devices (CADs) and Propellant Actuated Devices (PADs) are extensively used in aviation. Generally they are small devices in lightweight aluminium bodies and are difficult to demilitarise. Studies at Toole Army Depot[126] looked at utilising alkaline hydrolysis. They successfully used sodium hydroxide hydrolysis to dissolve the aluminium cases and convert the energetic material.

6.5.6.2 Actodemil®

Actodemil is a patented process of Arctech Inc. based in Chantilly, Virginia. The process is a form of alkaline hydrolysis using potassium hydroxide. In the Actodemil process the potassium hydroxide is combined with humic acid to form a reagent designated a-HAX. Humic acid is a complex organic acid with a molecular weight averaging from 1000 to 3000 g mol^{-1} and is obtained from coal. The process takes place at atmospheric pressure and moderate temperatures (70 – 90°C) and a batch typically takes two to four hours to process. After hydrolysis, the waste stream is neutralised using hydrogen peroxide.

Similar to other hydrolysis processes, the Actodemil process would normally take the energetic material as slurry feed after disassembly by some other means although aluminium body devices could be dissolved without pre-treatment. One particular claim for the Actodemil process is that the neutralised waste can be safely used as the Actosol fertiliser (see also section 6.6.4).[127]

The process has been tested on a wide variety of propellants and explosives. Plants using the process operate at:

- McAlester Army Ammunition Plant, Oklahoma,
- Radford Army Ammunition Plant, Virginia,
- In South Korea for US Forces, and
- A new facility at Crane Army Ammunition Activity with a capacity of one ton per day.

Figure 21 – Actodemil Unit at McAlester Army Ammunition Plant, Oklahoma[128]

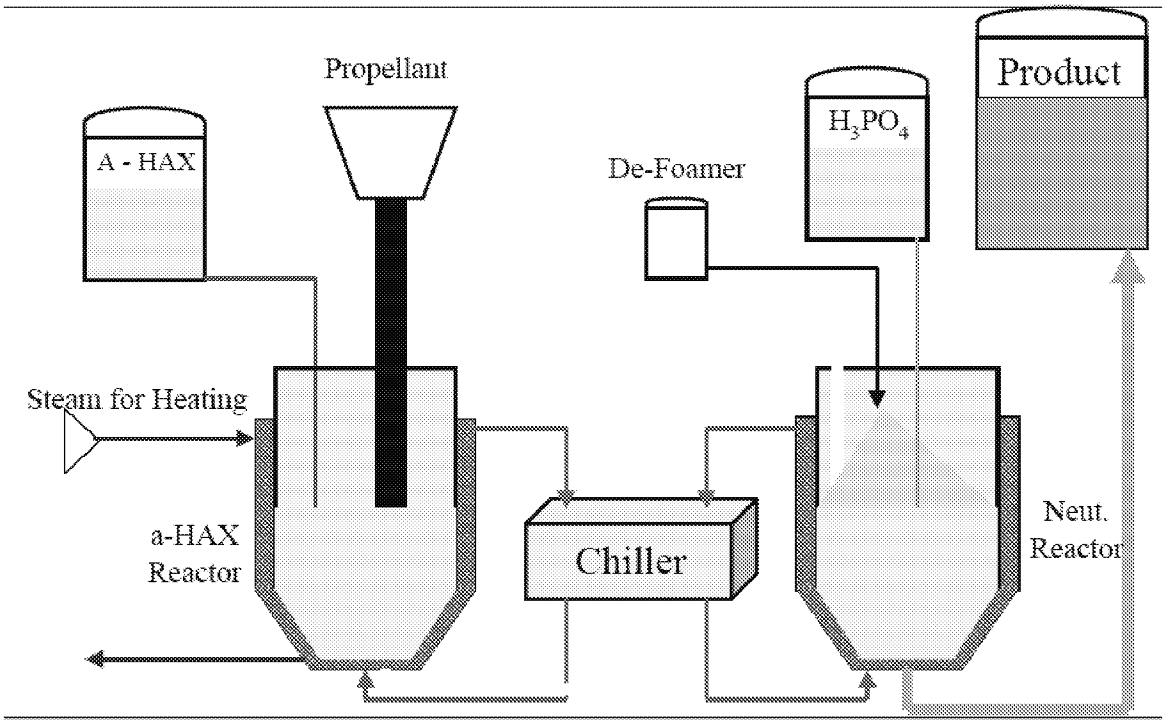

Figure 22 – Actodemil Process[129]

6.5.6.3 Supercritical Water Oxidation

Supercritical Water Oxidation (SCWO) uses the special properties of fluids and in particular water above its critical point. Supercritical fluids exhibit density between that of a gas and a liquid, high diffusion rates like a gas and reversal of solubility such that chlorinated organic compounds become highly soluble but inorganic salts are highly insoluble. For water the critical point occurs at 374ºC and 22.1 MPa and in the supercritical state water is a powerful oxidiser.

SCWO has a role in the destruction of particularly hazardous materials such as smoke and dye compositions and in treating waste water from other processes. SCWO requires a waste slurry for treatment so normally some form of pre-processing will be required.

Key issues with SCWO are:

- Design of reactors to cope with the extreme reaction conditions.
- Buildup of inorganic salts precipitated out due to solubility changes.

For these reasons it is likely to remain a niche capability. In the conventional weapons demilitarisation field, the US has operated a prototype plant at Pine Bluff Arsenal capable of processing 80 lbs (36.3 kg) of waste per hour.[130] The process has also been investigated for treating waste streams from hydrolysis systems.[131]

6.5.6.4 Molten Salt Oxidation

Molten Salt Oxidation (MSO) utilises a bath of liquid carbonate salts at 600ºC – 950ºC to treat waste streams. The carbonate salts provide excess oxygen which converts the energetic materials and other organic wastes to simple gaseous products by oxidation. MSO is seen as a potential replacement for incineration and has a number of advantages:

- The operating temperatures are comparable or lower than incineration and significantly lower then plasma arc techniques.
- Inorganic materials are trapped in the salt bath.
- The basic nature of the carbonate salt bath neutralises acidic gases.

These lead to the potential of lower emissions and a more environmentally friendly process. MSO was pioneered by Rockwell in the 1960s but most recent research and development has been undertaken by Lawrence Livermore National Laboratories (LLNL). LLNL have developed a number of plants including a demonstration unit at McAlester in Oklahoma which is capable of treating 30 lbs (13.6 kg) per hour and is shown in Figure 23.[132]

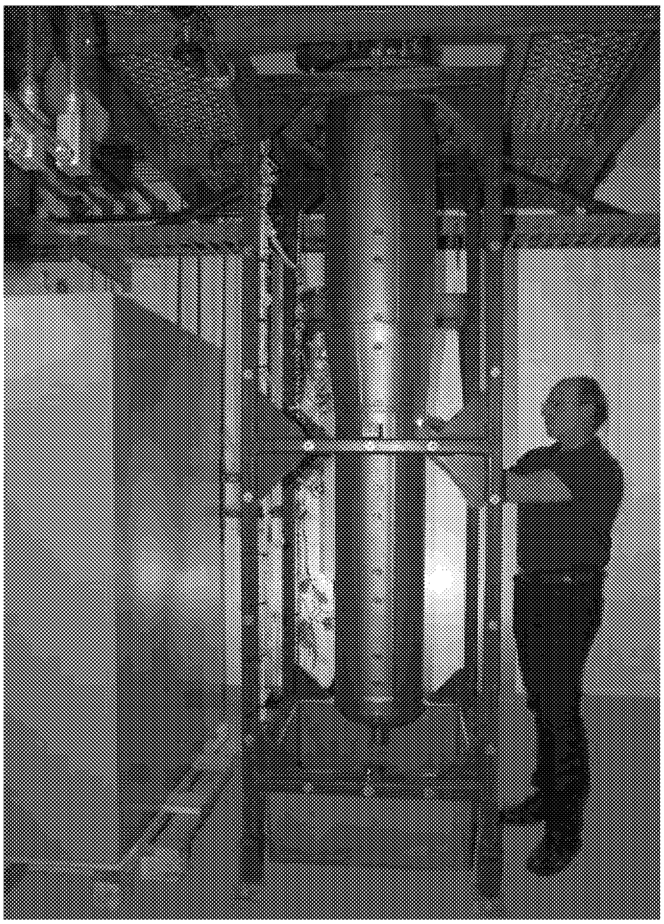

Figure 23 – Molten Salt Oxidation Plant at McAlester Army Ammunition Plant

Work has also been undertaken at NSWC Indian Head.[133] The Indian Head prototype is capable of processing in excess of 20 lbs (7.5 kg) per hour.

6.5.6.5 Mediated Electrochemical Oxidation

Mediated Electrochemical Oxidation (MEO) utilises a two-stage electrochemical process to convert energetic materials. MEO uses a metal ion (usually cerium, silver or cobalt) in a mineral acid electrolyte. The metal ion is oxidised at the anode and in turn becomes an oxidising agent for the energetic waste being treated.

A number of pilot plants have been built in the UK and the US and the along with hydrolysis and SCWO, MEO was a candidate for the Assemble Chemical Weapon Assessment programme using the AEA Technology Silver II process. As part of this evaluation, destruction of a number of explosive materials was demonstrated. The US Navy acquired a cerium based unit from CerOx Corporation in 1999 to evaluate the destruction of Otto Fuel II (a monopropellant fuel) contaminated waste.[134] They found that the system was limited, which was designed for disposal of liquid wastes, was limited by the insolubility of most solid explosives. They were unable to modify the plant to treat slurry wastes and concluded that MEO is too complicated and expensive for bulk treatment of energetic materials.

6.5.6.6 Wet Air Oxidation

Wet Air Oxidation (WAO), also known as the Zimmermann process, involves the use of oxygen as an oxidising agent, supplied by air at elevated temperatures and pressures (up to 320ºC and 22 MPa). WAO is a well established technique being patented in Sweden in 1911 and developed Frederick Zimmermann for production of artificial vanilla in the 1930s.[135] Although widely used for industrial wastewater treatments, the application to demilitarisation is more novel. Most research has been undertaken into the destruction of propellants. The US Army Corp of Engineers reviewed research into destruction of triple base propellants.[136] They concluded, from bench scale testing, that WAO was an effective technique and in particular could be used to treat the waste feed from alkaline hydrolysis.

6.5.6.7 Direct Chemical Oxidation

Direct Chemical Oxidation (DCO), also known as peroxydisulphate oxidation, involves the use of the powerful oxidiser peroxydisulphate at moderate temperatures and pressures. In 1999 Lawrence Livermore National Laboratories published a report into the destruction of TNT using DCO.[137] Using a small one litre reactor with an aqueous peroxydisulphate solution at 95ºC they successfully destroyed small amounts of TNT. The same report also looked at the use of catalysts and the destruction of ethlylene glycol and trichloroethane.

6.5.6.8 Adams Sulphur Oxidation

The Adams process involves the use of an elemental sulphur at elevated temperatures (around 450º to 600ºC) but at atmospheric pressure. The sulphur oxidises organic compounds producing simple sulphur compounds. Some are gaseous emissions however the remaining waste forms a solid carbon polymer which is advantageous from a treatment perspective. A summary of the process is given by Hendricks and Klimeck[138] Although considered in the 1993

Alternative Technologies for the Destruction of Chemical Agents and Munitions[139] it was considered unsuitable for processes with large amounts of waste water which would be typical of conventional demilitarisation.

6.5.6.9 Photocatalytic Oxidation

Photocatalytic or Ultra Violet (UV) oxidation involves the use of light energy to cause the break-down of organic substances. This method has been the subject of some research and a number of pilot plants. NASA looked at the techniques for the destruction of hydrazine contaminated waste water from the Space Shuttle programme.[140] The proposed UK 'Demil 2000' programme used UV oxidation as an intermediate step between alkaline hydrolysis and biodegradation in order to reduce the toxicity and increase the biodegradability of the hydrolysate.[141] The use of UV light is a considerable operating cost and therefore there has also been research into appropriate catalysts to allow the use of visible light.[142] As yet, the technique has not progressed to the production stage and appears to have less interest than other oxidation techniques.

6.5.7 Biodegradation

In contrast to chemical means like chemical oxidation, it is possible to destroy energetic materials by biological means. In general this technique is known as biodegradation or, particularly when referring to explosives contaminated soils, bioremediation. In essence, biodegradation involves an oxidation-reduction reaction and the breaking of bonds in organic energetic materials, however, unlike chemical oxidation this occurs due to the action of microbes. Biodegradation can be aerobic, where the microbe uses oxygen to accept electrons gained in the oxidation-reduction process, or anaerobic, where other substances such as nitrate and sulphate ions, some metals or carbon dioxide are used as electron acceptors. A good overview of the generic process of biodegradation can be found in the National Research Council's review of In Situ Bioremediation.[143]

Biodegradation has a number of advantages.

- It is regarded by the general public as a natural process when compared to incineration or chemical oxidation.
- It operates at ambient temperatures and pressures.
- It does not produce the range of pollutants such as dioxins that incineration can.

However, the most significant advantage occurs in the field of bioremediation. Here, in situ bioremediation allows the treatment of soil and groundwater without the difficulties associated with removal. This allows treatment under buildings and in deep aquifers with little disturbance.

Biodegradation is limited by the necessity to tailor the process to particular energetic materials and in addition it can be more difficult to control to completion than chemical methods. For example, biodegradation techniques can be subject to 'toxic upsets' which cannot occur with chemical oxidation techniques.

In general, nitrate ester and nitramine based explosives and propellants are not readily biodegradable. The US Army Corps of Engineers reviewed progress in biodegradation in 1998.[144] They found that:

- TNT can be biodegraded to varying degrees aerobically and anaerobically,
- RDX and HMX biodegrade better anaerobically,
- NG biodegrades aerobically stepwise to glycerol which can be biodegraded aerobically or anaerobically,
- NQ biodegrades anaerobically only, and
- NC is difficult to biodegrade but is susceptible after alkaline hydrolysis pre-treatment and also to fungal or compost biodegradation.

Basic research continues into biodegradation of energetic materials. Ringelberg et al. have looked at RDX bioremediation in cold climates[145] while Nishino and Spain have researched the treatment of DNT.[146] As this suggests, however, most interest is in bioremediation due to the huge advantages of in situ treatment. The following examples of techniques have been applied to demilitarisation in particular:

6.5.6.10 Aqueous/Slurry Biodegradation

This technique uses a bioreactor to treat a waste stream. The bioreactor allows the conditions to be carefully controlled and the waste stream can be introduced at an appropriate rate to ensure that the energetic materials are destroyed. An example of this approach can be found at ATK Thiokol's Utah plant where a bioreactor is run for the treatment of perchlorate waste streams from rocket motor production and demilitarisation. The plant was upgraded by Applied Research Associates Inc. to a capacity of 8000 lbs (3600 kg) per month. The process is illustrated in **Figure** 24 below.

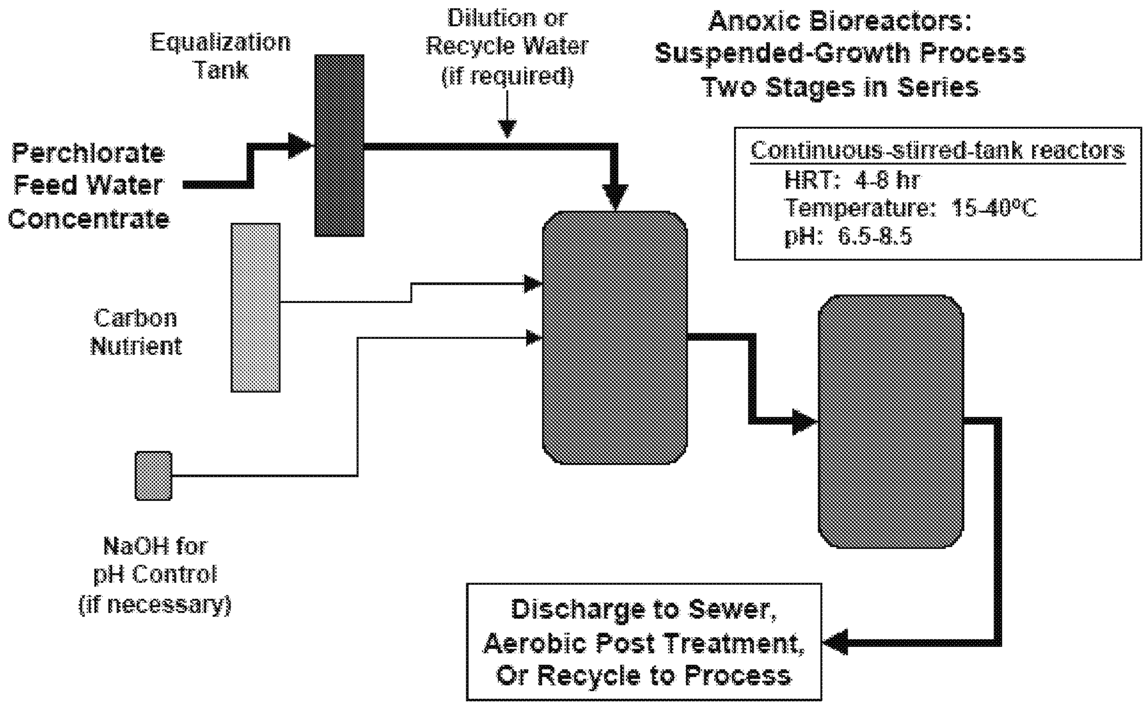

Figure 24 – ATK Thiokol Perchlorate Treatment Plant[147]

6.5.6.11 Enzyme Degradation

Enzymes are biocatalysts that accelerate biological reactions. In biodegradation they could be used to improve the speed of destruction for energetic materials. SERDP conducted a project into enzymatic degradation of TNT.[148] Although the research showed some potential the programme was ceased after two years in 2000. One particular problem encountered was the unknown toxicity of the products of TNT degradation.

6.5.6.12 Granular Activated Carbon – Fluidised Bed Reactors

The cost of using Granular Activated Carbon (GAC) to treat explosives contaminated waste streams is high due to the necessity of replacing and treating the GAC. GAC – Fluidised Bed Reactors (GAC-FBR) are a method of reducing the cost of this treatment through biodegradation. GAC-FBR combines the absorbency of activated carbon (see section 4.3.1) with the improved reaction characteristics of a fluidised bed process (see section 6.5.5.5). To this is added anaerobic biodegradation which breaks down the organic nitro compounds and significantly allows the GAC to be recycled into the system. A pilot plant with this technology was installed at McAlester Army Ammunition Plant and the resulting report[149] found that significant savings were possible over a conventional GAC process.

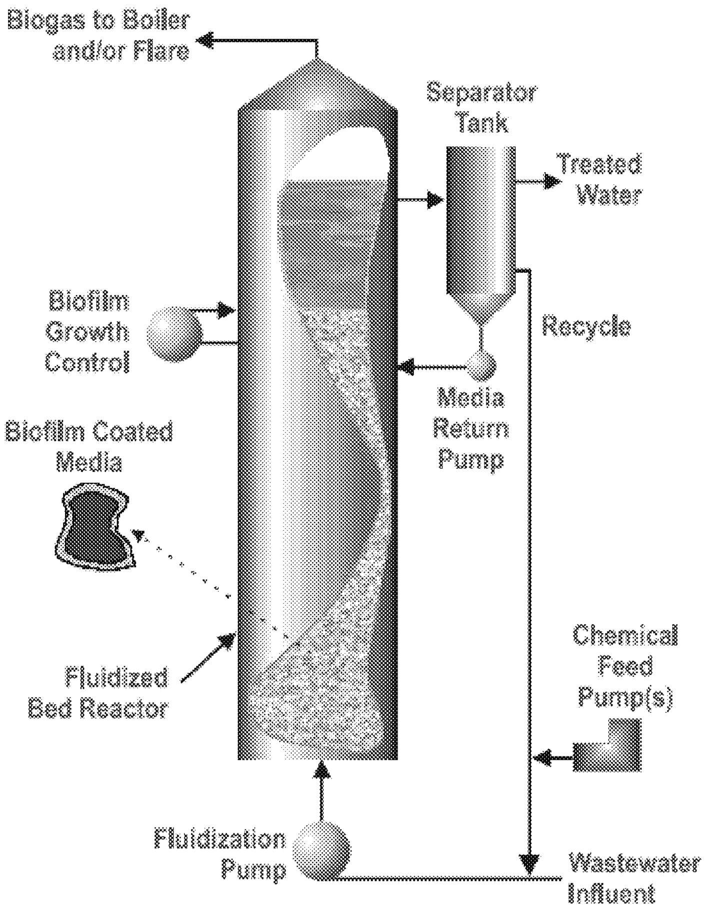

Figure 25 – Anaerobic Fluidised Bed Reactor[150]

6.6 R^3 APPLICATIONS

Although many of the techniques described previously allow a degree of resource recovery and reuse (R^3), a number of techniques and applications are concentrated on this aspect.

6.6.1 Resale

Traditionally, resale or gift was an option for disposal of excess munitions. Although this is still possible, concerns about proliferation of conventional weapons mitigates against the use of this as a principal method. In particular, the Wassenaar Agreement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies places restrictions on the use of resale as a disposal method.[151]

Resale also has no application to unserviceable munitions and the munitions typically placed for disposal may be difficult to sell if obsolete.

6.6.2 Energy Recovery

Energy recovery involves using the energetic qualities of the waste streams to reclaim energy. This can involve co-firing of slurries in boilers or fluidised bed combustors or can involve the recovery of waste heat such as a waste heat boiler to generate steam and electricity in the pollution control system of an incinerator.

6.6.3 Scrap Metal Recovery

One of the easiest forms of resource recovery is the reuse of scrap metal from munitions casings. Essential to this however is that the scrap metal is safe for reuse. Typically 'flashing' is used to remove traces of energetic materials or toxic substances from scrap metal before it are sold. This involves the heat treatment of the metal at approximately 400ºC and many incinerators can be used as flashing furnaces.

Before scrap metal can be released to commercial contractor, most nations have 'Free from Explosives' requirements to be met. These requirements are more codified in some countries than in others. A particular example of an explicitly codified system is the US. The US Department of the Army issues a pamphlet on the Classification and Remediation of Explosive Contamination.[152] This pamphlet defines four levels of contamination:

- 1X – articles which have only been subjected to routine, after-use cleaning and therefore substantial contamination continues to exist.
- 3X – articles where surface contamination has been removed but sufficient contamination may remain in 'less obvious' places to present an explosive safety hazard.
- 5X – articles where there is not enough remaining contamination to present an explosive safety hazard.
- 0 – articles that were never contaminated.

For demilitarisation, the 3X and 5X levels are relevant, defining the efficiency of the demilitarisation method and these descriptions are often found in the descriptions of demilitarisation techniques. Under US regulations, 3X articles cannot be sold to the general public but 5X articles may be. There is further guidance in the pamphlet on assessing the level of contamination.

Another aspect to be considered in the recycling of scrap metal is mutilation. A demilitarised munition may still look for all intents and purposes like a munition. If these are sent for scrap then there is the potential for unwarranted calls to Explosive Ordnance Disposal teams if they are 'found'. In addition, scrap dealers may not accept scrap that looks like munitions for fear of munitions that have been inadvertently left live. Dow[153] addresses this issue and reviews the current US standards for mutilation of munitions scrap.

6.6.4 Recycling as Fertiliser

Energetic materials generally have high nitrogen content, as a result that can be usefully recycled as fertilisers or components of fertilisers. A good illustration of this is the dual use of ammonium nitrate as the component of a commercial explosive (ammonium nitrate fuel oil or ANFO) and as a fertiliser. For military explosives and propellants some form of treatment is required before they are suitable to use as fertilisers. The most common form of treatment for this application is hydrolysis.

Due to the acute link between the use of fertilisers in agriculture and human health the reuse of industrial chemicals as fertiliser is regulated by national bodies. In the US, the Military Munitions Rule[154] clarifies the EPA's position on the recycling of propellant and explosives as fertiliser. This sets out three requirements to claim exemption from the Resource Conservation and Recovery Act (RCRA) and therefore avoid being treated as solid waste. These are:

- it must no longer exhibit the characteristic of reactivity;
- all underlying hazardous constituents must be treated in accordance with the Universal Treatment Standards (UTS); and
- if it exhibits the characteristic of toxicity then the appropriate treatments must be conducted.

Faessler and Emery[155] give an example of recycling of nitrocellulose fines in a fertiliser application. At the Badger Army Ammunition Plant (BAAP) in Wisconsin, 1.25 million pounds (567 000 kg) of nitrocellulose fines were stored wet in concrete storage pits from former production. The material was treated as a slurry with potassium hydroxide hydrolysis and then neutralised by hydrogen peroxide. The resulting fertiliser contained nitrogen, phosphorous and potassium and 1.24 million gallons (470 000 litres) were used on various crops and pastures. The cost for treatment of the nitrocellulose was over US$1 million less than the lowest incineration based bid and a further US$260 000 was saved in fertiliser costs.

The Actodemil hydrolysis process (see section 6.5.6.2) is particularly designed for production of fertiliser (Actosol). Actosol has been tested, and meets the Military Munitions Rule requirements.[156] Compared to the BAAP fertiliser which was a 1:1:8 product (approximately 1% nitrogen, 1% phosphorus, 8% potassium), Actosol when generated from nitrocellulose fines is a 5:5:15 fertiliser. Arctech Inc. provide

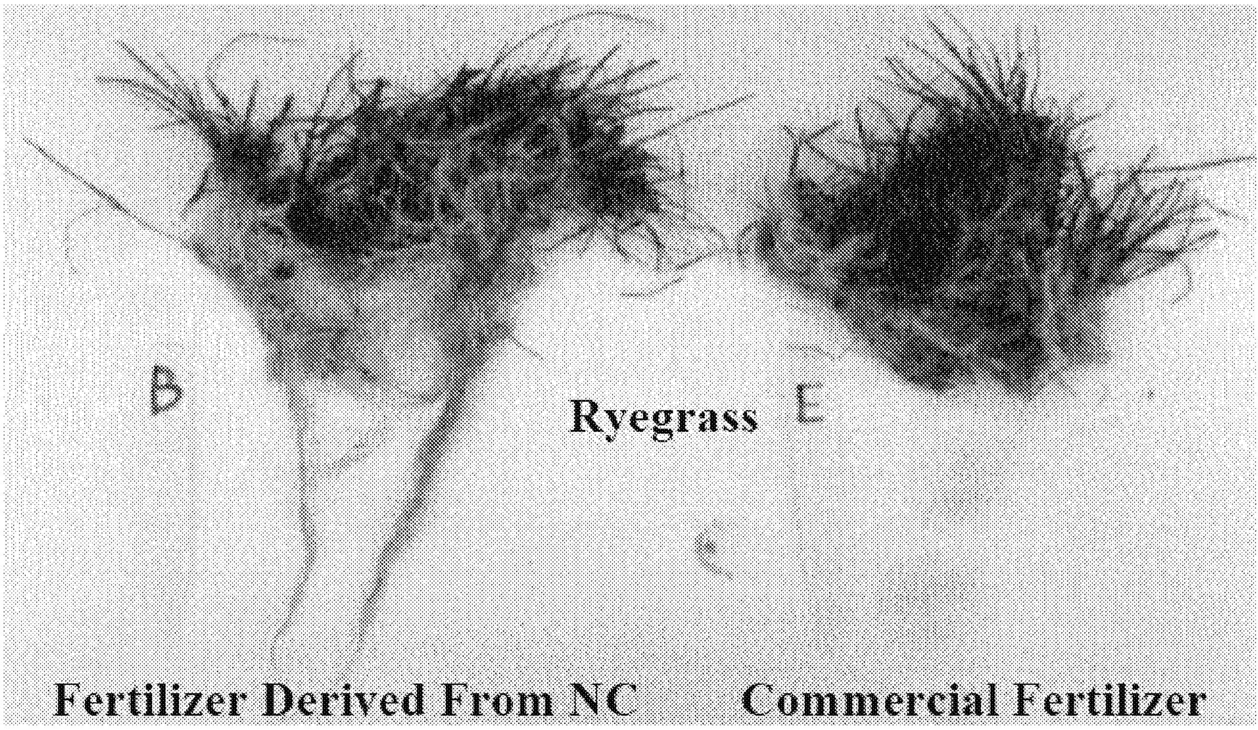

Figure 26 – Effectiveness of Actosol Fertilizer Derived from Propellant[157]

6.6.5 Chemical Conversion

Waste streams for demilitarisation can be recycled by chemical conversion into products that have a commercial market. The application is dependent on the particular material being recycled however the goal is to turn the relatively inexpensive demilitarisation product into a higher value product. Some examples are:

6.6.5.1 White Phosphorus

White phosphorus is an incendiary found in smoke generating rounds. It is hazardous and difficult to dispose of. In the US, the banning of open burning of smoke munitions in 1980 led to the incineration of white phosphorus munitions. As phosphoric acid is a commercially utilised product (in particular in soft drinks) and is produced by burning white phosphorus, investigations were undertaken to recover the phosphoric acid using a scrubbing system. A full scale plant was established at Crane Army Ammunition Activity (CAAA) in 1989 which handles all natures of US white phosphorus ammunition.[158] Facilities for recovery of phosphoric acid also exist in Europe where Alsetex have a modern plant in France and ISL have a plant in Germany.[159]

6.6.5.2 Conversion of Ammonium Picrate

The US has large quantities of Explosive D (ammonium picrate) in obsolete projectiles. A number of means have been developed to remove the ammonium picrate from the shells (see section 6.4.2.1). Treatment of the recovered ammonium picrate has concentrated on conversion to higher valued products.

NSWC Crane and Gradient Technologies developed a process for converting ammonium picrate to picric acid. Their patented process[160] involves the use of a strong acid (sulphuric acid) and an organic solvent (toluene). The picric acid has commercial applications, particularly in dye making. Gradient Technologies were expected to start processing a stockpile of one million pounds (454 000 kg) in 2003.[161]

Lawrence Livermore National Laboratory (LLNL) has investigated methods of synthesizing the explosive TATB from a diverse feedstock including ammonium picrate and picric acid.[162] These have been successful at pilot scale. TATB is a particularly expensive explosive to synthesise so the value added through this process is considerable.

6.6.6 <u>Energetics Recovery</u>

Although some energetic materials can be recovered directly by means such as drying of washout slurries, others require additional treatment. Typically this occurs in PBXs where binders can be difficult to separate from the energetic components. Some techniques for achieving this include:

6.6.6.1 Liquid Ammonia Extraction

The technique involves the use of liquefied ammonia as a solvent to dissolve energetic materials. The cross-linked rubber binders found in many rocket motors are insoluble and so are separated from the energetic materials. A pilot plant was established for MLRS rocket motors and following a successful trial, it was included in the Missile System Recycling Facility at Redstone Arsenal.[163]

6.6.6.2 Acid Digestion or Solvolysis

RDX and HMX can be recovered from PBXs with a process known as acid digestion or solvolysis. The process consists of two phases, in the first, the polymeric binder is solubilised using nitric acid for HMX or a mixture of water, calcium chloride and a surfactant (wetting agent) for RDX. Elevated temperatures in the order of 70 to 80ºC are required during this phase. In the second phase, the energetic material and the binder are separated by centrifuge. This process is patented by TPL Inc. and has been shown to provide very pure HMX (see section 6.6.9). A 150 lbs (68 kg) per day sub-scale plant has been tested and the HMX is considered to provide a cost advantage over commercially manufactured HMX but the RDX is considered to be uneconomic to recover at this point in time.[164]

The process also allows recovery of the acid/binder solution from HMX which when neutralised with ammonium hydroxide and dried generates Ammonium Nitrate / Polymeric Fuel which is viewed as a possible commercial blasting explosive. NEXPLO Bofors (now EURENCO Bofors) have also patented a solvent based process for extracting pure RDX or HMX from explosives.[165]

6.6.7 <u>Rheuse as Commercial Explosive</u>

Energetic materials removed by techniques such as washout and meltout can be reused as commercial explosives rather than destroyed. Commercial applications for explosives vary from mine blasting which requires cheap and easily transportable explosives such as ANFO to more demanding applications require military style explosives.

To compete with ANFO based commercial blasting gels, any demilitarisation product needs to be produced at a very low cost. TPL Inc. in the US has designed a number of blasting gel products based on demilitarisation of propellant.[166] These use large amounts of propellant (in excess of 60% of the composition) as the only energetic component of the blasting gel and provide superior performance to ANFO. TPL Inc. manufacture large quantities of their propellant based blasting gels at their Fort Wingate facility.

Higher value commercial explosives can be formulated using RDX/TNT based munitions. Applications include:

- Charges for gun barrel cladding,
- Shaped charges for underwater cutting, and
- Boosters for mining charges.

6.6.8 Reuse Propellant as Small Arms Ammunition

After removal, propellant can be reused in other applications. A direct reuse is as propellant in small arms ammunition. Generally this involves the remanufacturing of high performance artillery propellants and TPL Inc. in the US investigated this application.[167] They found that they could manufacture pistol ammunition from gun propellants but could not successfully commercialise the idea due to a lack of competitive advantage. As a result they shifted their focus to developing a flashless powder for small arms ammunition. This has been successfully trialled with a reduction in visible flash, smoke and recoil compared to conventional loadings.

6.6.9 Requalification for Military Use

One potential reuse application is for recovered energetics to be used in new munitions. Unlike commercial applications, this requires that the energetic material meet the qualification requirements for new explosives, in essence the material needs to be requalified. This is likely to be most practical for high value explosives such as HMX.

NSWC Crane examined HMX recovered by acid digestion from LX-14 at a TPL Inc. pilot plant.[168] The recovered HMX was characterised at NSWC Indian Head and LANL and met the specification requirements. The report notes that although in specification, the material was more acidic than, and exhibited slightly different particle size when compared to virgin HMX. The recovered HMX was used to prepare charges of PBXIH-135 which preliminary results indicate meets qualification requirements. The complete results are due in 2006.

A simpler task involves the reclamation of TNT. At McAlester Army Ammunition Plant in Oklahoma an autoclave meltout plant is used to remove TNT from munitions. These TNT is reclaimed and tested for compliance with the relevant specification. The key is the cost of the process as TNT is a fairly low value explosive. In this case, the US has limited TNT production capability and the reclamation is therefore valuable.

7. ORGANISATIONS

7.1 PROGRAMMES AND CONFERENCES

A number of conferences and meetings address the technology of demilitarisation.

7.1.1 NDIA Global Demilitarization Symposium

This annual symposium, organised by the Joint Ordnance Commanders Group (JOCG) and the National Defense Industrial Association (NDIA), is held in the United States every May. It is the premier demilitarisation symposium and attracts around 500 attendees. The focus is on US demilitarisation research however there are some papers presented from other countries.

7.1.2 Department of Defense Explosives Safety Seminar

This conference is organised by the US Explosives Safety Board. It is held annually in August. Among the wide range of papers presented are normally a number related to demilitarisation.

7.1.3 Swedish International Disposal Conference

Jointly organised by the Swedish Section for Detonics and Combustion and the Competence Centre for Energetic Materials it is held in November in Sweden but at irregular intervals. The fourth conference is due to be held in 2006. The conference covers a wide range of topics related to disposal and not just purely demilitarisation. The focus is on Swedish research however there are some papers presented from other countries.

7.1.4 FINNEX 2002

In 2002, the First International Seminar on Energetic Materials was organised by the Finnish Defence Forces Technical Research Centre (PvTT). The seminar included a section on demilitarisation and it is possible that future seminars will address demilitarisation as well.

7.1.5 International Chemical Weapons Demilitarisation Conference

Although focussed on chemical weapons, some papers presented at this conference are of interest to conventional weapons demilitarisation. It is organised by the UK Defence Science and Technology Laboratory (DSTL) and is held in a European country annually.

7.1.6 Applied Vehicle Technology (AVT) Panel – 115

AVT-115 is a NATO panel addressing the environmental impact of munition and propellant disposal. They are expecting to run a workshop in 2007. As well as demilitarisation aspects, they are interested in the effect of training activities.

7.2 GOVERNMENT AND NON-GOVERNMENT ORGANISATIONS

7.2.1 MSIAC Nations

AUSTRALIA

Defence Science and Technology Organisation (DSTO)
www.dsto.defence.gov.au

CANADA

Defence Research and Development Canada – Valcartier (DRDC-V)
Formerly Defence Research Establishment Valcartier (DREV)
North Val-Bélair, Quebec
www.valcartier.drdc-rddc.gc.ca

Areas of Interest/Research
- Site characterisation

FINLAND

Finnish Defence Forces Technical Research Centre (PvTT)
www.mil.fi/laitokset/pvtt/

Areas of Interest/Research
- Site characterisation

GERMANY

Fraunhofer-Institut für Chemische Technologie (ICT)
Pfintzal

Areas of Interest/Research
- Oxidation techniques
- Biodegradation

NETHERLANDS

Netherlands Organisation for Applied Scientific Research (TNO)
Prins Maurits Laboratory
Rijswijk
www.tno.nl

Areas of Interest/Research
- Mobile destruction of UXO
- Abrasive Waterjet Cutting
- Washout

SWEDEN

Swedish Defence Research Agency (FOI)
www.foi.se

UNITED KINGDOM

Defence Science and Technology Laboratory (DSTL)
Formerly Defence Evaluation and Research Agency (DERA)
www.dstl.gov.uk

UNITED STATES

Defence Ammunition Center (DAC)
McAlester Army Ammunition Plant, Oklahoma

Areas of Interest/Research

- Management of Joint Demilitarization Technology Programme

Naval Surface Warfare Center (NSWC) Crane Division
Crane, Indiana
www.crane.navy.mil

Areas of Interest/Research

- Abrasive Waterjet Cutting
- High Pressure Washout of Projectiles
- Microwave Meltout
- Induction Meltout
- HMX/RDX Recovery
- Gun Propellant Reuse
- Pyrotechnic Recovery
- Explosive D (ammonium picrate) Conversion
- Contained Detonation

US Army Armament Research, Development and Engineering Center (ARDEC)
Picatinny Arsenal, New Jersey
www.pica.army.mil

Areas of Interest/Research

- Plasma Arc Destruction
- Supercritical Water Oxidation
- Cryofracture
- Carbon Dioxide Blastout
- Advanced Autoclaving
- Ultrasonic Removal
- Pyrotechnic Recovery (Magnesium)
- Continuous Metal Emissions Monitor

Los Alamos National Laboratories (LANL)
Los Alamos, New Mexico
www.lanl.gov

Areas of Interest/Research
- Laser machining

Lawrence Livermore National Laboratories (LLNL)
Livermore, California
www.llnl.gov

Areas of Interest/Research
- Molten Salt Oxidation
- Laser machining
- Conversion of Explosive D

Sandia National Laboratories - California
Livermore, California
www.ca.sandia.gov

Areas of Interest/Research
- Explosive Destruction System (transportable CW system)
- Cryocycling
- Supercritical Water Oxidation
- Robotics for processing

7.2.2 Non-MSIAC

NATO Maintenance and Supply Agency (NAMSA)
Some NAMSA nations are not MSIAC nations and vice versa
L-8302 Capellan
Luxembourg
www.namsa.nato.int

Areas of Interest/Research
- Administers NATO Partnership for Peace Trust Fund demilitarisation activities
- Manages demilitarisation contracts for many NATO forces

United Nations Mine Action Service (UNMAS)
www.mineaction.org

Areas of Interest/Research
- Humanitarian demining
- Anti-personnel mine stockpile destruction

South Eastern Europe Clearinghouse for Small Arms and Light Weapons (SEESAC)

www.seesac.org

Areas of Interest/Research
- Stockpile destruction

7.3 COMMERCIAL

7.3.1 MSIAC Nations

FRANCE

SAE Alsetex
www.alsetex.fr

Capabilities or Areas of Expertise
- White Phosphorus reclamation facility

GERMANY

Rheinmetall Waffe Munitions (RWM)
www.rheinmetall-detec.de

Capabilities or Areas of Expertise
- Experience in demilitarisation of East German Army

Industriepark Spreewerk Lübben (ISL)
www.spreewerk.de

Owned by Spezialtechnik Dresden GmbH who in turn is owned by General Atomics Inc.

Capabilities or Areas of Expertise
- Thermal Destruction Facility at Lübben

Entsorgungsanlagen Betriebsgesellschaft mbH (EST)
www.est-steinbach.com

Owned by Spezialtechnik Dresden GmbH who in turn is owned by General Atomics Inc.

Capabilities or Areas of Expertise
- Incineration Facility at Steinbach, Saxony

ITALY

UEE Italia
Subsidiary of UEE

Esplodenti Sabino
www.esplodentisabino.com

SWEDEN

DYNASAFE AB
www.dynasafe.com

Capabilities or Areas of Expertise

- Mobile Static Kilns

EURENCO Bofors
www.eurenco.com

Capabilities or Areas of Expertise

- Solvolysis

UNITED KINGDOM

QinetiQ
www.qinetiq.co.uk

Capabilities or Areas of Expertise

- Demilitarisation facility at Shrewburyness

UNITED STATES

Arctech
www.arctech.com

Capabilities or Areas of Expertise

- Actodemil oxidation process

ATK Thiokol
www.atk.com

BlazeTech Corporation
www.blazetech.com

Capabilities or Areas of Expertise

- Atmospheric Dispersion of Reactive Agents (ADORA) model applicable to OB/OD

DeMil Internation
www.ch2m.com
Subsidiary of CH2M Hill

Capabilities or Areas of Expertise

- Donovan Blast Chamber

Chemical Compliance Systems Inc.
www.chemply.com

Capabilities or Areas of Expertise

- Munitions Analytical Compliance System (MACS)

- Emissions Databases

EBV EEC
www.ebveec.com

Capabilities or Areas of Expertise
- Demilitarisation facility in Joplin, Missouri

El Dorado Engineering, Inc.
www.eldoradoengineering.com

Area of expertise
- Explosive Waste Incinerators
- Microwave meltout

General Atomics
http://demil.ga.com
Owner of Spezialtechnik Dresden GmbH

Capabilities or Areas of Expertise
- Cryofracture
- Cryowashout
- Cryocycling
- Supercritical water oxidation

Gradient Technology

Capabilities or Areas of Expertise
- Abrasive Waterjet Cutting

Teledyne-Brown Engineering
www.tbe.com

Capabilities or Areas of Expertise
- Mobile Detonation Chamber System

TPL Inc.
www.tplinc.com

Capabilities or Areas of Expertise
- Demil facility at Fort Wingate, New Mexico

MULTIPLE

Nammo
www.nammo-demil-division.com

Capabilities or Areas of Expertise

- Norwegian Ammunition Disposal (NAD) operates an underground detonation facility in Norway
- Nammo-Buck operates a large demilitarisation facility at Pinnow in Germany

Non-MSIAC

CZECH REPUBLIC

VTUVM Slavecin
www.vtuvm.cz

DENMARK

DEMEX
Subsidiary of NIRÁS International
www.demex.dk

Capabilities or Areas of Expertise

- Demolition and mine clearance
- Consultancy on demilitarisation

SPAIN

Faex
Subsidiary of UEE

SWITZERLAND

RUAG Munition
www.swissmun.com

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